# OUTLINES OF THE OCCURRENCE AND GEOLOGY OF PETROLEUM

D. B. TARAPOREVALA SONS & CO. PRIVATE LTD.
210, Dr. DADABHAI NAOROJI ROAD, BOMBAY 1.

First published 1925

Printed and published by R. J. Taraporevala for D. B. Taraporevala Sons & Co. Private Ltd., 210, Dr. Dadabhai Naoroji Road, Bombay 1, at their Electrographic Industries Division, Apte Industrial Estate, Worli, Bombay 18.

# PREFACE

As the title suggests, this handbook is elementary in character, and the main object is to furnish an outline of the general features concerning the occurrence and geology of petroleum or bitumen, in a condensed manner, and with especial reference to practical interest; in the hope that it may serve as an introduction to those desiring to become acquainted with the subject (or students in oil-geology), and that it may also be of some interest to the large class who are concerned in its economic or commercial aspects.

The exigencies of the present day demand the expeditious summing up of the prospects as to properties or oilfields, in order either to commence operations without delay, or to cut the expenditure with a minimum of loss—in cases where the prospects are not of sufficient promise to warrant further outlay. Instances are many where much detailed exploratory work and protracted and elaborate geological surveys, conducted in unpromising areas, have, after much expenditure, only led to disappointing or negative results (although much of scientific interest may have been gained), while costly expeditions have been dispatched to regions concerning which the information already available is sufficient to indicate that there can be but small hope of a successful issue. In addition, drilling is often carried out in hopeless ground and many companies floated on behalf of evidently valueless lands. These circumstances suggest that the present attempt to meet the needs of the non-specialist may not be altogether unacceptable.

The discussion herein is limited to the more pertinent theoretical questions and practical considerations, or the general topics of interest; and, where possible, is illustrated by reference to known examples in the field. Recourse has naturally been made to, and much information derived from, the various works and papers bearing on the subject, but, as references to such have been made by means of footnotes to the text, it has not been deemed necessary to enumerate them here; although the materials and the views expressed are also founded on personal observations and studies made in various regions during two decades.

The part discussing the origin was, in substance, originally published in the form of a paper appearing in the *Mining*

*Magazine* (in 1920), although, as now presented, it has received modifications and additions. The short sketch, appearing in the Introductory chapter (§ 2), that relates to the available sources of supply, is largely derived from an article (also by the writer) that was published some years ago in the *Academy*. This is, nevertheless, now included, as it may perhaps lead to some suggestions as to where to look to for further supplies or as to what regions may disclose new oilfields.

This work was projected and commenced some time ago, but several interruptions have delayed its eventual completion for publication. This deferment, however, has rendered it possible to add an Appendix on "Geophysical Methods as applied to Oil-Finding," by Dr. M. Mühlberg, who has had the advantage of discussing the several aspects of the subject with Prof. J. Kœnigsberger, and thus of having been able to rely on the experience of this well-known authority.

This new branch of applied economic science has unquestionably a future before it, and more attention to its development is to be desired in this country; while already important and successful results have, in several places, been achieved through the deductions made therefrom. Although suitable topographical and geological conditions are desirable for the favourable application of some of the geophysical methods—as, *e.g.*, in the case of the gravitative methods—it is often just in those instances where the requisite conditions obtain, that exclusively geological data are lacking—as in flat country or plains—and that consequently other means of obtaining evidence are to be desired.

In conclusion, thanks are due to Mr. R. Bullen-Newton, I.S.O., F.G.S., of the British Museum, for assistance given in looking through and criticizing the stratigraphical portions and also—in a similar connection—to Dr. M. Mühlberg, Ph.D.; and, for photographs of scenes in Alberta, Burma, and Sinai, to Mr. A. W. Dingman, of Calgary, Major T. R. H. Garrett, M.A., F.G.S., and Mr. T. Sutton-Bowman, B.Sc., F.G.S.; and, lastly, to the Publishers, Messrs. Charles Griffin & Co., Ltd., for their assistance, and for including this unpretentious volume in their Mining Series.

# CONTENTS.

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## CHAPTER I.

### INTRODUCTORY.

CONTENTS (1) "What is Bitumen?" Scope and Use of the Term Petroleum and the General Terms used for the Principal Descriptions of Bitumen in regard to Physical State—Diversity and Variation in the Chemical and Physical Properties—The Great Carbon Group—The Bituminous and Carbonaceous Series of Native Hydrocarbons: Their Relations and Distinctions—The Nomenclature, Classification, and Definitions of Terms as applied to the Various Forms of Bitumen and Allied Substances and the Confusion in the Terminology—Table of general Classification of the Native Hydrocarbons. (2) "Available Sources of Supply and Increasing Demand" Development of the Industry and Increase in the Use and Number of Commercial Products derived from Petroleum—Life and Duration of existing Supplies, and Prospective or Possible Localities and Sources of Supply for the Future—Russian Territories—Other Countries—British Domains—Progress in Economic Geology as applied to Oil-mining—Application and Development of Geophysical Methods in this Connection. (3) "Scope of the following Chapters" The Fundamental Principles of Geology that need Acquaintance or Recognition.

(1) **What is Bitumen?**—It was originally thought appropriate to describe the title of this subject as dealing with the geology and occurrence of "bitumen," this term being taken in the generic sense—*i.e.*, as comprising all the natural hydrocarbons of the bituminous series, whether in a solid, a liquid, or a gaseous state: for the study of the occurrence of petroleum is inseparable from that of the other descriptions of bitumen in a different physical condition, which are connected with or result from it, and may also give rise to it.

Owing to the circumstance, however, that the term "bitumen" is used—or misused—with different meanings, being often taken to denote only the solid substances, and owing to the consequent ambiguity, it was thought not unlikely that such a title might occasion some misconception as to the nature of the subject that is being treated. This primarily deals with the occurrence of petroleum, or mineral oil, which, from the standpoint of economic interest, is the principal variety of bitumen concerned, although it is at the same time necessary to consider the other forms of bitumen which are so intimately connected with it.

The view is here adopted that the term "bitumen," although it be used with various and conflicting meanings and receives varying definitions from different authorities, should be applied properly in its widest sense, in order to designate all the natural hydrocarbons of the bituminous series, whether in the solid, the liquid, or the gaseous condition, while the generic sense of the name, which is, of course, taken from the Latin term "*bitumen*,"* would seem to be in accordance with the ancient or original usage of the word.

The term "petroleum," however, is not uncommonly used in a generalized manner, to comprise all the substances connected with it, although this word—if literally interpreted should correctly be reserved for the bitumens in the liquid state. The term "maltha" (taken from the Greek word "μάλθα"—which denoted a mixture of pitch and wax used for caulking ships †) is used to describe those bitumens which are of an inter-

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mediate consistency, or physical condition—as also the term "mineral tar." While, in order to distinguish the solid bitumens, the word "petrolite" has been created, as a comprehensive term comprising the several varieties.

It is not possible, however, to draw any hard and fast line between the different forms of bitumen on a basis of physical condition or properties, such varying and merging one into the other, while there are all gradations passing from the infusible to the readily fusible solid bitumens, through the semi-solid and viscous descriptions—or "malthas," to liquid petroleum, and even from oil into gas.

There is, moreover, much variation in the chemical properties, as also complexity in the composition, of the bitumens. They are thus somewhat difficult of classification, for which purpose it is necessary to take into account a combination of both the physical and the chemical properties, together with the consideration of the geological mode of occurrence; although a primary division—on a chemical basis—can be demarcated, in the distinction of the paraffinaceous substances from the other bitumens.

The vast series of minerals and compounds in which carbon plays the principal part, as found in the earth, are characterized by much diversity and variability in their physical and chemical properties, and there are few that possess a composition constant enough in order to denote a definite mineral species; so that they have for the greater part to be regarded as indefinite admixtures, in which carbon, hydrogen, and oxygen are the chief constituents. The carbon group may be primarily classed as (1) The Pure Carbon Series, (2) The Carbonaceous or Coal Series, and (3) The Bituminous Series—the two last-named being mainly composed of hydro-

carbons; and the various members of the entire group range widely in physical properties—such as hardness and molecular cohesion, from the hardest known mineral (the diamond) to substances which are plastic, liquid, and gaseous; passing through graphite to the coal series, on the one hand, and to the bitumen series on the other. The latter series, however, is characterized by wider diversity in physical conditions, with a range from infusible solids as hard as the coals to viscous substances, liquids, and gases.

There is also gradation, through the infusible bitumens, from the carbonaceous to the bituminous series, and it is difficult to demarcate an exact dividing-line between them (some substances existing over which there has been controversy as to whether such should be classed as a coal or as a bitumen). In a general way, however, the bitumens are chemically differentiated from the coals by being comparatively rich in hydrogen and substantially free from oxygenated bodies; they also differ from the coals by containing larger amounts of volatile hydrocarbons. Indeed, the bituminous series, as a whole, is characterized by the greater diversity and range in physical properties presented by its various members. The coals, moreover, have as a rule higher specific gravities than those possessed by the various descriptions of solid bitumens, while they are also less uniform in composition. But, here again, the geological mode of occurrence and the origin afford the most important indications for distinction.

The subject of the nomenclature of the various forms of bitumen and the classification of the bituminous series, in which so much confusion and ambiguity has arisen, is further dealt with in the concluding chapter of this work—where the solid bitumens are considered, only brief allusion being now made to it.

The name "asphalt" (derived from the Greek word ασφαλτος" *—originally used to describe the occurrences of asphalt in the neighbourhood of Babylon) is another term which is employed with several meanings, and has become ambiguous. Thus, it is sometimes used to describe "impregnations" of bitumen, in rocks or deposits, or mixtures with some amount of mineral matter, in contradistinction to those forms of bitumen that occur in a purer condition with comparatively little intermixture of mineral matter—such as the high-grade "native" bitumens. Some investigators, however, have adopted a differentiation dependent on the fusing-point, and class under the term "asphalt" the bitumens (excluding "ozokerite" and those containing paraffins) of comparatively low melting-point (say, less than 250° F.), as also the viscous and semi-liquid descriptions. (To those that have a high fusing-point the name of "asphaltites" has been given.) Again, in commercial usage the word "asphalt" has come to imply the artificial commodity. The expression "asphalt," moreover, is also sometimes used in order to impart a chemical significance, as a generic title to differentiate the non-paraffinaceous bitumens from those containing paraffins (such as "ozokerite" and the oils of a "paraffin base").

The writer, however, prefers a distinction based on the geological mode of occurrence or formation, in the employment of the word, and to use the term "asphalt" for the bitumens accumulated on, or arising from inspissation (as from seepages) at the surface, as distinguished from those forms of bitumen that have been deposited and solidified within the rocks below (as in fissures or veins), and that are of subterranean origin. The bitumen of the former category is often much intermixed with mineral matter, or occurs in the form of

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Some distinguishing title is wanting in order to embrace all the varieties of solid bitumen belonging to the latter category, or the so-called "native bitumens" (although the term "meta-asphalt" was suggested, by Dr. Taylor of Philadelphia, a long time ago for this purpose, but does not seem to have since come into use).*

The descriptions of solid bitumens having a high fusing-point (over 250° F.), as represented by "gilsonite," "glance-pitch," or "manjak," and "grahamite," have by some been termed, and classed under the title of, "asphaltites," while the infusible types, as principally represented by "wurtzilite," "elaterite," "albertite," and "impsonite," have been described under the title of "asphaltic pyrobitumens," but the use of the term "pyrobitumen" in the description of such bitumens is somewhat undesirable (as tending to confusion with the pyrobitumens proper, belonging to a different series of minerals and comprising the coals, shales, etc.), although they may be regarded as affording a connecting-link between the bitumens and the pyrobitumens. The term of "kerite" has been applied to those solid bitumens that are insoluble in carbon disulphide, but these are more or less the counterpart of the infusible types.

The variability and gradation in physical and chemical properties together with the circumstances that some

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bitumens more closely related in chemical composition differ more widely in physical properties, and *vice versâ*, render these substances difficult of classification. It is, therefore, expedient for the purpose of classifying them, to take together the salient physical and chemical characteristics—as, *e.g.*, fusibility, specific gravity, percentage of fixed carbon, and solubility, in conjunction also with consideration of the geological mode of occurrence and formation—making a differentiation at the outset on the last-named basis, according to the manner above described, *i.e.*, as common superficial asphalt or otherwise. Although the substances containing paraffins —ozokerite and the mineral waxes—admit, on a chemical basis, of being separated into another primary division.

A differentiation based on the fusing-point, as between asphalt and "asphaltite" and the types of the latter, does not comply with the geological modes of occurrence, more especially as in many cases of the occurrence of pure bitumens in seams and veins the fusing-point of the substance decreases with depth, so that the fusibility at lower levels may have become that which would be used to define the substance as an asphalt.

Sometimes the terms "pitch" and "tar" are used to describe natural bitumens, but these words should properly apply to the products of destructive distillation; although there is not any objection to the employment of the expressions "mineral pitch" and "mineral tar" for solid bitumens and "malthas" respectively, while the term "glance-pitch" is used to denote certain varieties of solid bitumen.

The word "naphtha" is another name that is used somewhat vaguely, and with different meanings. It is often employed to denote benzine or petroleum spirit, but is presumably derived from the Greek word "νάφθα" —or the similar Latin word, which signified native oil or

## Natural Hydrocarbons.

| Bituminous Series. | | | | Carbonaceous Series. |
|---|---|---|---|---|
| Solid. | Viscous or Semi-solid | Liquid. | Gaseous. | |
| (*Petrolites*).<br>(1) Asphalt ("*Bitumenites*").<br>(2) The various and purer forms of solid bitumens (meta-asphalts) (including "asphaltites," and "asphaltic pyrobitumens" and "kerites").<br>(3) Ozokerite, and the paraffinaceous class. | Maltha (Pissasphalt)<br>Elaterite. | Petroleum (Asphaltic, paraffinaceous, and mixed-base oils) | Natural and petroleum gases. | Coals, lignite, etc. |

*Note.*—The "Pyrobitumens" include the coals together with the oil-shales. In some classifications, however, the infusible solid bitumens, or "asphaltic pyrobitumens," as they have been termed, are placed under the "Pyrobitumens," although these substances are obviously—by reason of their mode of occurrence and origin—more allied to bitumen than to the coals.

petroleum, while the Russian word for crude oil is derived from the same root (as likewise the Arabic and Persian "naft").

In conclusion, "Bitumen" may be broadly classified as in the table on the previous page.

Finally, the question frequently arises as to whether bitumen can be denominated a mineral or not. According to the restricted definitions put forward by mineralogists, it would not rank as a mineral, although coal has (by courtesy) received that title. But, if it be not a mineral, what should it be called? or under what name can it be designated in a general way? The substances of which the Earth's crust is constituted are either rocks, minerals, or the imbedded and petrified organic remains known as fossils. Bitumen in itself, except in the form of the impure asphaltic intermixed deposits and rock-impregnations, could not very readily be looked upon as a rock, and is neither of sedimentary origin nor a mineral or crystalline aggregate: while, although of organic origin, it could not well be defined as a "fossil" being a product of a chemical process and action, with subsequent migration and metamorphosis: but coal might more reasonably be regarded as a fossil.

If, therefore, coal is ranked as a mineral, bitumen has more claim to be termed such—even though often of indefinite or unstable composition. At any rate, it should be regarded as an economic mineral, as should the winning of petroleum or bitumen, whether solid, liquid, or gaseous, be regarded as appertaining to a branch of mining.

### (2) Available Sources of Supply and Increasing Demand.

The last quarter of a century has witnessed a remarkable and accelerating advance in the use of the various products and commodities derived from bitumen, more

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The variability and gradation in physical and chemical properties together with the circumstances that some

* The term "bitumenite" is suggested for this distinction (although this name was used by Prof. Traill in 1853 to describe "torbanite," but has not been continued for that use).

bitumens more closely related in chemical composition differ more widely in physical properties, and *vice versâ*, render these substances difficult of classification. It is, therefore, expedient for the purpose of classifying them, to take together the salient physical and chemical characteristics—as, *e.g.*, fusibility, specific gravity, percentage of fixed carbon, and solubility, in conjunction also with consideration of the geological mode of occurrence and formation—making a differentiation at the outset on the last-named basis, according to the manner above described, *i.e.*, as common superficial asphalt or otherwise. Although the substances containing paraffins —ozokerite and the mineral waxes—admit, on a chemical basis, of being separated into another primary division.

A differentiation based on the fusing-point, as between asphalt and "asphaltite" and the types of the latter, does not comply with the geological modes of occurrence, more especially as in many cases of the occurrence of pure bitumens in seams and veins the fusing-point of the substance decreases with depth, so that the fusibility at lower levels may have become that which would be used to define the substance as an asphalt.

Sometimes the terms "pitch" and "tar" are used to describe natural bitumens, but these words should properly apply to the products of destructive distillation; although there is not any objection to the employment of the expressions "mineral pitch" and "mineral tar" for solid bitumens and "malthas" respectively, while the term "glance-pitch" is used to denote certain varieties of solid bitumen.

The word "naphtha" is another name that is used somewhat vaguely, and with different meanings. It is often employed to denote benzine or petroleum spirit, but is presumably derived from the Greek word "νάφθα" —or the similar Latin word, which signified native oil or

## NATURAL HYDROCARBONS.

| Bituminous Series. | | | | Carbonaceous Series. |
|---|---|---|---|---|
| Solid. | Viscous or Semi-solid | Liquid. | Gaseous. | |
| (*Petrolites*).<br>(1) Asphalt ("*Bitumenites*").<br>(2) The various and purer forms of solid bitumens (meta-asphalts) (including "asphaltites," and "asphaltic pyrobitumens" and "kerites").<br>(3) Ozokerite, and the parafinaceous class. | Maltha (Pissasphalt)<br>Elaterite. | Petroleum (Asphaltic, paraffinaceous, and mixed-base oils) | Natural and petroleum gases. | Coals, lignite, etc. |

*Note.*—The "Pyrobitumens" include the coals together with the oil-shales. In some classifications, however, the infusible solid bitumens, or "asphaltic pyrobitumens," as they have been termed, are placed under the "Pyrobitumens," although these substances are obviously—by reason of their mode of occurrence and origin—more allied to bitumen than to the coals.

petroleum, while the Russian word for crude oil is derived from the same root (as likewise the Arabic and Persian "naft").

In conclusion, "Bitumen" may be broadly classified as in the table on the previous page.

Finally, the question frequently arises as to whether bitumen can be denominated a mineral or not. According to the restricted definitions put forward by mineralogists, it would not rank as a mineral, although coal has (by courtesy) received that title. But, if it be not a mineral, what should it be called? or under what name can it be designated in a general way? The substances of which the Earth's crust is constituted are either rocks, minerals, or the imbedded and petrified organic remains known as fossils. Bitumen in itself, except in the form of the impure asphaltic intermixed deposits and rock-impregnations, could not very readily be looked upon as a rock, and is neither of sedimentary origin nor a mineral or crystalline aggregate: while, although of organic origin, it could not well be defined as a "fossil" being a product of a chemical process and action, with subsequent migration and metamorphosis: but coal might more reasonably be regarded as a fossil.

If, therefore, coal is ranked as a mineral, bitumen has more claim to be termed such—even though often of indefinite or unstable composition. At any rate, it should be regarded as an economic mineral, as should the winning of petroleum or bitumen, whether solid, liquid, or gaseous, be regarded as appertaining to a branch of mining.

### (2) Available Sources of Supply and Increasing Demand.

The last quarter of a century has witnessed a remarkable and accelerating advance in the use of the various products and commodities derived from bitumen, more

especially petroleum. In the first place, there arose the large and increasing demand for the lighter fractions, or the products of low volatility, occasioned by the requirements of light-oil engines, or motors. The heavier products have also been sought in rapidly increasing quantities for the purpose of steam-raising in the form of liquid fuel (which has been found to possess many points of superiority over coal), and presents especial advantage in the case of naval vessels (particularly when on active service). Later, the use of the heavier oils has been extended by the advent of the heavy-oil engine, notably by that of the Diesel type.

Moreover, in consequence of the increasing requirements of machinery, as well as the progress of railway-building, lubricating oils have become increasingly needed, and such lubricants are mainly derived from the heavier products of petroleum. In addition, many other products of essential importance have been in ever-increasing demand. Among such may be mentioned paraffin wax, ceresin, and vaseline, as well as the various miscellaneous products or by-products—such as, among others, the "okonite," obtained from the residue in refining ozokerite, which substance is extensively employed as an insulator; also "heel-ball," and "carbon black" (the latter being obtainable from natural gas as well as oil).

With this large expansion in use, it appeared at one time not unlikely that the demand for petroleum might outstrip the supply, at the present rate of production; and consequently anxious enquiries have from time to time been made with reference to the quantities available in various parts of the world, and as to the duration of existing supplies, while doubts have been expressed in some quarters that sufficient petroleum exists in order to meet future requirements. Many persons, including

eminent authorities, have opined that the possible supplies must soon prove insufficient, and that the existing stores of petroleum cannot last very long; there was, in fact, not so long ago, what might be called a "scare" in regard to the sources of petroleum for the future—reminiscent of the coal scare of many years ago.

Dr. Engler was reported to have mentioned one hundred years as the probable duration of the available supplies, while another well-known authority has computed the "oil age" as not much longer than half a century. If it were necessary to depend only on existing supplies, then there might be some ground for apprehension in that direction, although the majority of the existing oilfields are capable of much extension—in many cases vertically as well as laterally. A glance, however, at the map of the world should suffice to dispel such gloomy prognostications as to the future, and to show that there is much scope for further developments and possibility of future discovery. On taking into account the relative smallness of the areas which have been already prospected, and the still smaller areas that have been actually tested by borings, the vast unexplored regions where conditions favourable for the presence of petroleum may prevail, as also those where the physiographical features appear to indicate favourable conditions, it will at once be apparent that the existing oilfields, and, indeed, all the regions that have been explored for petroleum, represent but a small proportion of the territories that may be capable of producing oil. The science of oil-finding, moreover, is still comparatively in its infancy. With the advance of this knowledge, as well as the spread of civilization, and the consequent extension of the facilities of transport to various regions, it is not improbable that considerable stores of petroleum, previously unknown, may eventually become available.

If Russia alone be considered, it is evident that the districts where petroleum is, at the present time, known to occur, represent, in all probability, but a very small fraction of those regions that may be capable of containing commercially valuable deposits. The belts of Tertiary strata which flank the Caucasus on each side were mostly formed under conditions suitable for the occurrence of petroleum, and it is highly probable that conditions and formations favourable for its accumulation may be present in many localities—other than those where it has already been found—in either of these zones. Moreover, strata of earlier age (*e.g.*, Cretaceous) also show in several parts of this region a petroliferous character, and may eventually prove to be productive. The distance from the Caspian Sea to the Black Sea is some 550 miles; while the northern Tertiary belt extends much farther westwards—as far as the Crimea; also, for a considerable distance northwards, to the vicinity of Stavropol.

So far, the localities where petroleum has been discovered or exploited in this region are comparatively few and widely separated; for instance, besides Baku and some few other localities in the vicinity of the Caspian Sea, these are principally represented by Grozny, Maikop, Taman, and Kertch, on the north, and Chatma and Naphtalan on the south, of the main range of the Caucasus.

Then, again, the basin surrounding the Caspian Sea appears to contain, for the greater part, conditions favourable for the presence of petroliferous formations, save for the few interspersed areas, where igneous rocks or crystalline limestones occur. Up to the present, besides Baku on the west, the prolific island of Tcheleken on the east, and the more extensive Ural Caspian district on the north-east—where commercial deposits of Pre-

Tertiary age are found, comparatively little has been exploited or even explored in these regions.

Furthermore, the large region of Transcaspia should contain extensive formations which may reasonably be believed to be, in some parts, of a petroliferous nature, while up to the present nothing has been done between the neighbourhood of the island of Tcheleken, with the adjacent portion of the mainland, and Ferghana, in Eastern Turkestan, some 950 miles away to the east, or between the latitude of that line and the Persian frontier; further, the basin of the Aral Sea and the neighbouring territories are as yet unprospected, and these may be productive of some commercially important results.

Farther northwards, there is the extensive region situated in the basin of the Volga, where there are numerous, although somewhat widely separated, indications of petroleum, and some yield may probably in the future be obtained from sections of this region. Farther north again, in the district of Uchta, still older strata, of Devonian age, are found to be petroliferous, where some exploiting operations have already been started with success.

Thus, in Russian territory alone, even leaving out of account the vast and little-known tracts of Siberia, there is every justification for anticipating that large stores of petroleum are available for future discovery, such as would be adequate to meet all predictable future needs.

But it is not, of course, only Russia that would be looked to for future requirements, although the prospects for developments there appear to be among the most promising.

There are still to be found large regions, imperfectly explored or unprospected, in many parts of the globe, where conditions suitable for the occurrence of petroleum

may prevail. For instance, in the vast and still inadequately known continent of Africa, there are yet many regions little known or explored, and where the tropical jungles may hide localities of petroliferous indications; while the same may be said of large tracts of South America. Such also is the case of the several large islands of the Eastern Archipelago, some of which have already come to rank among the most important producing countries, although as yet relatively little has been there developed; and large areas, covered by dense vegetation, still remain unexplored. Possibilities likewise exist in Siam, in the northern densely wooded territories of which petroliferous indications occur, and some primitive workings were there conducted by Chinese. While the greater part of the vast realm of China has up to now been little prospected or tested (save for some exploitation and trials carried out by the Chinese in a few localities, as well as the operations in the salt-district of Szechuan). Finally, there certainly exist large promising areas, awaiting development, in Venezuela; as also prospective fields in other South American States, *e.g.*, Colombia, Argentina, Bolivia, and Chile (as well as further scope in Peru and Ecuador).

Much has often been said regarding the importance of obtaining petroleum from the British Dominions and of the comparative scarcity in them. But here again there does not seem to be much ground for pessimism. Among the extensive British territories in Africa there may, not improbably, occur workable deposits. There is also much scope in Canada—particularly in the western provinces, while the north-western and northern territories are awaiting development; otherwise the circumstance that the international boundary divides the greatest oil-producing country in the world from one—at least as far as Western Canada is concerned—where

little or no production is obtained, would be a strange coincidence. There are, moreover, to be found many places—particularly in the regions at the eastern foot of the Rockies—where deposits might be reached by deep-boring, when this has been rendered more practicable or less costly and liable to misadventure, by the progress and evolution of the drilling art. In the West Indies, other British domains and islands in the Archipelago, besides Trinidad, are not unlikely to be capable of producing petroleum. Again, in dark New Guinea, largely hidden by dense jungle and unexplored, petroliferous strata are found in several localities, in some of which exploratory operations and some trials have already been carried out; while there remain, of course, large areas that are not yet explored or touched. Furthermore, some favourable results might not improbably be obtainable in New Zealand, should efficient prospecting or testing operations be there carried out. Finally, there is room for further development and considerable extension in Burma; while little has been done in this direction in the Federated Malay States, where, in some areas, the geological conditions are not unfavourable and scientific prospecting may lead to the discovery of petroleum—particularly in the more recently ceded States of Tringganu, Kelantan, and Kedah.

In view, then, of all the foregoing considerations, there should be no reasonable doubt that adequate supplies of petroleum will be forthcoming from various parts of the world, in order to satisfy future requirements. And this apart from the possibilities of enhanced production by the distillation of oil-shales. To that industry improvements in, and the advance of, scientific methods for producing and refining oil from shale, and for eliminating sulphur and other impurities and the utilisation

of by-products, may give great expansion, and even afford a more exact and less speculative method of obtaining petroleum, while also permitting the profitable extraction of oil from shales of a relatively low grade. With the oil-shales, however, it is not proposed here to deal.

Concurrently with the advance in the use and the increase in the demand for petroleum, the necessity and importance of applying geology to petroleum exploration and for the location of underground accumulations has, during the past two decades, been gradually becoming recognized, although formerly the use of geology in oil-finding was but too frequently belittled by the so-called "oil-man," while even now it is in some quarters insufficiently appreciated. At the same time, too, this economic branch of applied geology has made considerable advances, although it is still somewhat young in experience, and much yet remains to be ascertained; while more, doubtless, will be revealed by future discoveries.

So different are the circumstances, associations, and requirements in the study of the occurrence of petroleum and in oil-mining from those of other kinds of mining, that what might be regarded as a special economic science has arisen and become indispensable.

More recently, there has become recognized the advantage obtainable from the application of physical science, for ascertaining geological data by means of "geophysical methods," and progress made in the development of such methods; and a new economic science—requiring the co operation of both the physicist and the geologist—has come into existence. By this means, not only may important supplementary data be obtained, where the conditions are suitable for the operation of the new methods, but the underground

conditions may be thereby discovered in localities where geological evidence alone may disclose little or nothing —or is lacking or entirely wanting. Although as yet in an early stage, the application of geophysics to oil-finding has already achieved some successful results, and by such means it is not improbable that oil-deposits, which otherwise would remain unknown, may come to be discovered. Notwithstanding the circumstance that some of the instruments which have been devised and are required for the operation of these methods are at present somewhat costly, it is obvious that such observations are a less expensive procedure than "wild-cat" drilling.

The geophysical methods may be grouped in the following principal categories :—(1) Gravitative, (2) Magnetic, (3) Electrical, (4) Acoustic and Seismic, (5) Thermometric, and (6) Radioactive.

Although practical geophysics is as yet still in an early stage of development, the time may not be far distant when it may be possible, by means of the co-operation of these several classes of methods, and thus ascertaining and taking together the respective physical properties of the rocks or deposits to reach a more or less exact determination of what is beneath.

(3) **Scope of the Following Chapters.**—Although, as already indicated, this small treatise is essentially of an elementary character, a previous acquaintance with the fundamental principles of Geology is desirable. It is, for example, necessary that the importance of denudation should be fully appreciated, and it should be recognized that almost everywhere enormous masses of rock have been removed from the land, by the denuding agents, or "epigene forces," that tend to reduce all land-surfaces to a base level of erosion.

Likewise, it is desirable that there should be a comprehension of the great terrestrial movements and disturbing agencies, or "hypogene forces," and their effects, whereby the rocks of the Earth's crust have been folded and dislocated, and surfaces have risen and subsided; as also an understanding of the structural features that have thereby been occasioned.

Moreover, an acquaintance with the general principles of stratification, and with the various periods of geological history, and the divisions by which the sedimentary rocks are classified, is necessary.

# CHAPTER II.

## THE ORIGIN OF BITUMEN.

CONTENTS.—General Remarks and Importance of Study and Researches in this Direction — Inorganic Hypotheses — Marine Organic Hypothesis—Animal Origin—Micro-organic Hypothesis—Association of Salinity with the Occurrence of Petroleum—Terrestrial Vegetation Hypothesis—Possibilities of Derivation from Coal—Resinous and Wax-like Substances therein—Origin from Marine or Aquatic Vegetation—Oil-shales, etc. — Dynamo-Chemical Origin — Deductions and Conclusions,

ALTHOUGH to a great extent dependent on chemical investigation, the subject of the origin of bitumen is essentially concerned with geological inquiry and speculation. It is obviously a question of great economic importance and demands further researches, especially as much in relation to the mode of occurrence must remain insufficiently understood, until more decisive knowledge is attained concerning the genesis, so that such would tend to increase possibilities in oil-finding.

It is by no means attempted here to present anything approaching an exhaustive account of the many hypotheses which have from time to time been advanced to elucidate this still somewhat obscure subject, but merely to give a brief discussion, from a geological aspect, of various theories and evidence, with personal observations and conclusions.

Up to the present time, it cannot be said that any hypothesis has given universal satisfaction, or been accepted as conclusive. It is, however, probable that no single theory of origin suffices to meet the case.

The theories of origin may, of course, be in the first place broadly grouped as either organic or inorganic. It appears, however, highly improbable that any commercial supplies of petroleum can have originated in an inorganic manner, although in some cases where small quantities or traces of hydrocarbons occur in association with igneous rocks, or with volcanoes, it may have arisen in this way. There is consequently no need to dwell at any great length on this mode of origin here.

## INORGANIC ORIGIN.

Small amounts of hydrocarbons have been found in meteorites, which circumstance has given rise to the theory that such substances existed in the original material of the Earth, or what has been termed the "cosmic" theory of origin, as advanced by Sokolov,* who also adduced in support the occurrences of bitumen in igneous rocks and the presence of carbon and hydrogen in the pyrospheres of celestial bodies. It may be mentioned in this connection that it has been found possible to obtain small quantities of hydrocarbons from igneous rocks,† for instance, granite, gabbro, gneiss, basalt, etc., in which hydrocarbons are present, usually in the gaseous condition.

In respect of inorganic hypotheses, it may perhaps not be necessary to describe the notable theories which were formulated by Mendeleev,‡ or include the theory suggesting an origin from the action of percolating carbonated waters on metallic iron at a high temperature deep down beneath the surface of the Earth (the higher

* *Bull. Soc. Imp. Nat. Mosc.*, ser. 2, vol. iii., pp. 720-739 (1890).

† Tilden, W. A., *Proc. Royal Soc.*, vol. ix., pp. 453-457 (1897).

‡ *Jurn. Russk. Phiz. Khim. Obsck.*, vol. ix., Otd. i., pp. 36-37 (1877), and vol. xv., Otd. i., pp. 367-380 (1883). *Bull. Soc. Chem. de Paris*, vol. i., p. 501.

specific gravity in the interior of which might be due to the presence of metals), or the hypothesis founded on the circumstance that the action of water, or steam, on metallic carbides, can produce hydrocarbons. In view of the high specific gravity of the Earth, it was thought that such carbides might largely exist beneath the surface. However, the existence of improbably large quantities of metallic carbides, within access in the Earth, would be required, if only to suffice for originating the amount of petroleum which has been produced, as the amount of metallic carbides demanded is very great in proportion to the petroleum that can be produced from them. Furthermore, the circumstances that large deposits of bitumen or petroleum are only found in the stratified rocks, that the deposits found in the strata of younger age predominate, and that very frequently barren porous beds are intercalated in the petroliferous beds, or the strata subjacent to an oil-series do not contain petroleum, all tend to constitute evidence contrary to the supposition of the deep-seated origin.

Attempts have been made to show a connection between the distribution of oilfields and regions of abnormal magnetic variations, and that the latter may be due to the presence beneath the surface of magnetic metallic carbides, this view being considered compatible with the theory of origin from metallic carbides. It appears certain, however, that no such marked correspondence, between the positions of oilfields and irregularities in the lines of magnetic variation, is generally to be found.†

Another inorganic hypothesis is that which is sometimes called the "mining" ‡ theory of origin and has

* Becker, G. F., *Bull.* 401, *U.S. Geol. Survey*.
† Tarr, W. A., *Econ. Geol.*, vol. vii., No. 7, pp. 647-661 (1912).
‡ Wade, A., *Geologists' Assoc.*, vol. xxiv., pt. i. (1913).

been suggested in view of the frequent association of sulphur and gypsum with petroleum. It endeavours to explain the origin of petroleum by the action of the gases sulphur dioxide and sulphuretted hydrogen on limestone which, when water is present, could produce petroleum, gypsum, and sulphur; * while, incidentally, the origin of the gypseous deposits, which are in so many localities associated with petroleum (either in massive beds, as in the Red Sea and Persian areas, or in veins, and in the form of crystalline selenite, as in many other localities, for instance, Russia, Trinidad, etc.), could be in like manner explained, as also the frequent presence of sulphur in the oils.

It is probable, however, that the gypsum found in association with petroleum has generally been formed in a stratiform manner or is contemporaneous with the beds in which it is found, especially when it occurs in intercalated beds of great thickness (for instance, in the Samara Division of Russia, and in the Red Sea and Persian areas), while sometimes organic remains are enclosed by it. Moreover, gypsum (or the crystalline form, selenite) is of very frequent occurrence unaccompanied by hydrocarbons, as in many clays, for instance, the Ampthill Clays and others in Britain; also in massive deposits, as in the older non-petroliferous series in Trinidad.

Before leaving the subject of inorganic hypotheses, it may be recalled that some time ago O. Fisher, quite independently of any surmises as to the origin of petroleum, while discussing the condition of the infracrustal regions of the Earth's interior, with a view to meeting certain astronomical questions concerning the rigidity of the Earth and the absence of appreciable tidal per-

* Ross, O. C. D., *Rep. Brit. Assoc.*, Section C, 1891, p. 639; Hume, W. F., *Cairo Scient. Journ.*, vol. iv., No. 48, p. 14 (Sept. 1910).

turbations in the Earth's crust, advanced the theory that there was a liquid sub-stratum saturated with gases which were dissolved in the molten magma, it being supposed that the compressibility of the gases would account for the absence of measurable tides in these regions of the planet, and thus remove the principal argument for rigidity.* It was at the same time considered probable that the gases might be hydrogen or compounds of hydrogen.

## ORGANIC ORIGIN.

Turning now to the organic hypotheses of origin, there are, of course, both animal and vegetable possible sources, and such hypotheses might be subdivided into those of marine or aquatic animal organisms and micro-organisms (both animal and vegetable), of marine vegetation, and into that ascribing the derivation to terrestrial vegetation.

It has been chemically demonstrated, notably by Engler and Höfer,† that, under certain conditions of temperature, pressure, and confinement, it is possible to produce liquid hydrocarbons from animal remains. The former obtained petroleum-like products by distillation from menhaden oil, fish, and mussels. Moreover, bitumen has been found associated with fossil mollusca and corals, and traces of petroleum have been found in fossil fishes. Petroleum has also been found in association with coal (although many such cases may be due to impregnation), while products resembling natural hydrocarbons have been obtained by the action of superheated steam upon wood.‡ Furthermore, it is possible to obtain petroleum

* Fisher, O., "Physics of the Earth's Crust," 1889.

† "Das Erdöl," 1919; *Min. Journ.*, vol. cvi., No. 4,118 (1914); *Ber. Deutsch. Chem. Ges.*, xxi., pp. 1816-1827 (1888); xxii., 592-597 (1889).

‡ Orton, E. *Bull. Geol. Soc. Amer.*, vol. ix., pp. 80-100 (1898).

in small quantities from peat, and from certain kinds of sea-weeds; and also from diatomaceous and other oozes.

It is thus apparent that there are many organic raw materials which can originate bitumen under suitable conditions, among which is that of their being relatively quickly covered up by deposits.

Striking support is given to the hypotheses of organic origin—both animal and vegetable—by the optical characters of petroleum, as evinced by its behaviour in polarized light, as originally shown by Rakuzan.* Petroleum, as occurring in nature, is most usually optically active (that is, it rotates the plane of polarized light), while similar hydrocarbons of chemical production are not optically active (that is, they are isotropic). Exception, however, has been found in some oils, usually among the light, pale descriptions,† for instance, in some from Surakhani, Caucasus, and Velleia and Montechino, Italy, and also one variety from Japan.‡ This characteristic was supposed to be due to the presence in natural petroleum of small quantities of the alcohols cholesterol ($C_{24}H_{46}O$)—one of the zoosterols, and the phytosterols, the former of which occurs in the animal fats and oils, while the latter (sitosterol, $C_{27}H_{46}O$, etc.) is found in vegetable oils.§ As cholesterol is supposed to be the most usual ingredient, and to be representative of the larger amount of organic sources, it has thereby been

* *Jurn. Russk. Phiz. Khim.*, xxxvi., p. 554 (1904), xxxvii., pp. 79-85 (1905), and xxxviii., p. 1129 (1906).

† Incidentally, this circumstance would seem to support the view that, in the cases (comparatively rare) of the occurrence in Nature of such very light oils, such may be due to natural distillation, since the greater part of the cholesterol—when distilled—is found to be associated with the higher boiling fractions, while also lower fractionations from the same substance have been found to be optically inactive.

‡ Rakuzan, M. A., *Ibid.*, xxxix., p. 634 (1907).

§ Lewkowitsch, J., "Chemical Technology of Oils, Fats, and Waxes, 1913, vol. i.

considered that animal products must have furnished the principal origin. Later investigations, however, have tended to cast some doubt on the view that the general presence of these substances in all petroleums has been clearly established.'

While it appears probable that in many cases and conditions marine animals or the smaller marine organisms may have given rise to the occurrence of bitumen or petroleum, and such would seem the most feasible hypothesis, it is, however, by no means advisable to aver an exclusive marine-animal origin for all petroleum or bituminous deposits. It is also quite possible that vegetable remains (terrestrial as well as marine) may, in certain instances, have been a not unimportant contributing factor in providing petroleum and bitumen, either in conjunction with the animal agencies, or possibly sometimes independently.

**Marine Organic Hypotheses.**—In support of a marine organic agency of origin, it may be asserted that petroliferous beds occur in many regions in strata deposited under marine conditions, where terrestrial vegetation could not have been readily available, and sometimes, but rarely, even under deeper-sea conditions. Moreover, proofs of abundant marine life are frequently existent in series of deposits in which bitumen occurs. In many regions, for instance in the petroliferous areas in Russia, abundant remains of marine organisms, such as molluscs, echinoids, corals, etc., as well as those of the smaller marine organisms, and sometimes of fishes, occur in the beds associated with the petroleum; while in many petroliferous strata, as in California and elsewhere, abundant remains of the smaller marine organisms (animal and vegetable), such as foraminifera and diatoms, as well as algæ, exist. It is difficult not to connect the

* Redwood, B., "A Treatise on Petroleum," 1913, vol. i., p. 281.

former abundance of those organisms with the occurrence of petroleum, more especially as traces of petroleum-like oils have been obtained from similar organisms living at the present day and in marine muds of organic detritus, as in the gulfs of Mexico, Suez, etc. Again, the occurrence, in New Brunswick (Canada), of abundant remains of fossil fishes, associated with the bituminous shales and albertite," is striking and suggestive.

**Marine Animal Origin.**—In connection with a marine animal origin, an observation made by the writer of a curious but suggestive occurrence in the deltaic regions of the Mahakan River in Koetei, Dutch East Borneo, may be mentioned. Attention was called by some natives to the occurrence of small quantities of petroleum in a well in a locality near a creek of the delta and situated on extensive alluvial flats, the presence of the oil rendering the water unfit for drinking. The occurrence of petroleum in such a situation appeared strange, as the nearest Tertiary beds were at a considerable distance, and even there the petroliferous horizons had sunk to a considerable depth beneath later Tertiary beds which were not petroliferous; moreover, the alluvial deposits in the vicinity of the well, which was not far from a deltaic estuary, should be of considerable thickness, and include argillaceous material. It did not, therefore, seem probable that the oil could have infiltrated from below to that position; furthermore, there were several other wells which had been dug by the natives for water on this alluvial flat, and none of the others displayed traces of petroleum. The oil occurring in this well appeared of a clear and fresh nature, and unlike that of the usual seepages found in the petroliferous Tertiary formation; the drops could be seen rising from the bottom. Accordingly, in order to investigate this occurrence, the writer had the well drained of water and dug deeper. After

a while a collection of remains of many mollusca, corals, and echinoids was disclosed, which appeared to occur in a sort of pocket and were intermingled with fine sand; it was evidently an aggregation or shoal which had formerly been washed together. All the organisms were saturated with this peculiar pale but strongly smelling petroleum,* the associated sand being comparatively less saturated. On some of the bivalves being opened, they were found to contain fine sediments strongly saturated with this oil. The absence of any traces of petroleum in the surrounding sands and alluvium, but occurring only in association with these marine remains occurring in a pocket, would suggest a connection between the two circumstances. The organisms proved to be of Post-Pliocene age.

Another somewhat remarkable circumstance was also noticed by the writer in North-West Borneo, on the Klias island. A test-pit was dug to a depth of about 40 feet in soft dark-grey shale. No traces of petroleum were found in the hole until a depth of about 35 feet had been reached, when a strong seepage appeared in a corner of the hole, and hard rock was found in the same place. Further excavation revealed the rock to be a large block of hard and compact coral-limestone, not *in situ*, which was present on the side of the hole. On the limestone being broken with a pick an escape of gas took place, and the exudation became stronger, it being found that it came from the limestone block which was saturated with petroleum. Over a gallon of a very light and clear oil, which contained a large fraction of spirit-constituents and was highly inflammable, was gradually obtained from the exudation during the course of several

* Some of this oil was collected and afterwards examined, it being found to be similar to petroleum.

† The specimens were examined by Mr. R. Bullen Newton, F.G.S., of the British Museum.

days. This occurrence is mentioned, as the circumstances are peculiar, inasmuch as the block of limestone (which was compact and not very porous) was not connected with other limestone or associated with any petroliferous bed from which it could have derived the oil by infiltration; and if it had formerly been broken off a limestone which was originally petroliferous, it does not appear likely that it could have retained so much petroleum and gas before it became sealed by the surrounding clayey shales which must have been of comparatively slow deposition. The only other alternative to an indigenous condition would be the derivation of the petroleum from finely divided organic matter in the shales, it having concentrated, by adsorption or capillarity, in the limestone, although it would be difficult thus to explain the presence of so much gas under pressure.

Similarly, petroleum has been found associated with coral-reefs, for instance, in the Red Sea,* in positions where it could not very well have had an extraneous origin.

A difficulty in the hypothesis of origin from marine animals, principally, however, affecting the case of the larger organisms having hard parts, is found in the usual absence in the actual petroliferous seams of their tests, shells, or other remains, although this would only be in case of the assumption that the petroleum is indigenous to the beds in which it is found. Moreover, in petroliferous series, where some beds contain abundant remains of marine organisms, as in Russia, these do not usually themselves exhibit traces of liquid hydrocarbons or bitumen, but the petroliferous seams are generally found separated from them, although often present in the immediate neighbourhood or in superjacent positions.

* Fraas, Dr., *Bull. Soc. Scient. Nat. Neuchâtel*, T. viii., pp. 58-61 (1868).

It is, however, probable that, in the case of most deposits, the petroleum is adventitious, not having often originated at the horizons at which it is found, but migrated to other beds, where greater porosity favours its accumulation and storage.

In order to meet such conditions as those mentioned above, it could be contended that the petroleum had been entirely expelled, by means of volatilization or distillation, from the horizons containing the organic materials which produced it, and, a suitable medium or sufficient outlet for gaseous emanation having been available, had condensed in and permeated superjacent porous beds protected by an impervious cover. Sufficient heat, by which the hydrocarbons might have been volatilized, could have been generated by the folding movements and pressure in the strata and consequent friction, which may not have produced so much heat in loose porous beds as in the more compact and finer-grained limestones, marls, etc.; furthermore, an increase in pressure in the upper porous beds, as the rising gases became imprisoned beneath their impervious cover, may have also aided condensation in them. Or this process may likewise have been performed by slow distillation * at a low temperature.

Such migration in the gaseous condition, however, could not be readily considered feasible in the case of heavy oils with solid residues, as in the case of the great majority of deposits, although the very light oils, which are found at various places (for instance, at Surakhani, in the Apscheron peninsula, and at Tabaquite, Trinidad, etc.), have probably been thus produced. Moreover, some residual traces of bitumen would in such a case be expected to remain, associated with the organic remains in the original beds.

* As suggested by Newberry, J. S., "Geology of Ohio," vol. i., p. 158 (1873).

It is, however, possible for migration and expulsion to be also effected in the liquid state (the solid residues being included or dissolved in the oil) by means of capillary attraction and adsorption, or by being squeezed out under pressure into adjacent porous beds; as also, in the case of the original rock or deposit being at all porous, by hydrostatic action and hydraulic pressure.

It is remarkable how quite heavy petroleum can thus penetrate seemingly impervious argillaceous rocks, while it may also be caused to pass through cracks, or thin fissures, such as small slip-planes or joint-planes, etc., sometimes in this manner traversing considerable thicknesses of strata.

A remarkable example of this migration through great thicknesses of argillaceous material is found in Trinidad, where inspissated petroleum has in places penetrated the Miocene clays through a great thickness, having risen up cracks, such as in minor slip-planes, joint-planes, or other minute fissures, along which asphaltic residues have often been deposited; while it also appears to have permeated, or become diffused through, portions of the rock by means of adsorption.

Another method and different manner of migration —by sedimentary transportation—will be considered later.

The origin cannot always lie in the seat of occurrence, more especially as the petroleum is rarely confined only to a single bed or horizon of a series; but usually it is found that most, and often all, of the porous beds in the series have become impregnated—that is, in the area where they occupy positions affording suitable structural conditions.

Moreover, petroleum-deposits generally occur, with some notable exceptions, in ferruginous sands, grits, or even coarser-grained rocks and conglomerates, the

conditions during the deposition of which would not have favoured the organic life that has furnished the source.

In some instances, porous limestones, as for example, the detrital limestones of the Persian Gulf and Red Sea regions, the fissured limestones of Tamasopa and San Felipe in Mexico, and those of the Corniferous and Niagara, and the dolomitic Trenton Series in North America, act as the oil-bearing strata; and in the last-named cases have been considered to constitute the seat of origin,* although such occurrences might, of course, be due to impregnation.

It may be noticed, however, that no less an authority than H. von Höfer † expressed the opinion that petroleum is indigenous to the beds in which it is found.

The lack or paucity of phosphates in petroleums or in the containing deposits has been considered as an objection to animal origin,‡ although, as regards the absence of phosphates in the beds, calcium phosphate is, of course, generally present to a certain extent in sedimentary rocks (otherwise the luxuriant vegetation conspicuous in so many regions where petroleum is found could not thrive). Moreover, the petroleum-accumulations represent concentrations from extensive areas, while they are in most cases adventitious.

Furthermore, calcium phosphate is soluble in saline water, and also to a certain extent in water containing carbon dioxide (whereby the plants, dependent on phosphates, are able to absorb it). The frequent association of salt or saline deposits with petroleum, suggestive of an origin under saline conditions or in desiccated basins, will be further considered later. Carbon dioxide may

* Sterry Hunt, T., "Geology of New York," vol. iii., p. 334; Orton, E., "Report on the Occurrence of Petroleum and Asphalt Rock in W. Kentucky," 1891, p. 43.

† *Min. Journ.*, vol. cvi., No. 4,119 (1914).

‡ Cunningham Craig, E. H., "Oil Finding" (1914), p. 9.

also have been present, and was probably a product in one of the stages in the formation of petroleum. It is, therefore, possible that much of the calcium phosphate may have been carried away in solution.

If extensive phosphatic deposits or nodules are to be expected wherever animal remains have been plentiful in deposits, the same might be expected in the case of all limestone strata.

In regard to the absence of phosphates in the petroleum itself, in the peculiar process of decomposition, or reduction (perhaps influenced by a special kind of bacterial action to which further reference will be made, whereby the hydrocarbons were produced), gaseous or volatile hydrides might have been formed. The presence of phosphorus, however, has been found in some oils.

Likewise, the lack of nitrogenous substances in petroleum has been regarded as incongruous with an animal origin, although the vegetation-hypotheses would also be thereby affected. Nitrogen, however, is a common constituent of natural gas,* while nitrogenous compounds or bases are generally found in solid bitumens,† and are usually present in crude oils, in small but very variable amount, in some cases reported to vary according to facility for exposure or to increase with depth.‡

It seems, however, possible—in the manner suggested by Engler and others—that the nitrogenous tissues may have been first affected and most of the nitrogenous substances removed in the particular processes of decomposition, in which bacterial action probably played

* In some cases, gases containing as much as 80 per cent. in Kansas, and even nearly 98 per cent. in Oregon, have been found, but such are, of course, abnormal. *Cf.* Henderson, J. A. L., *Journ. Inst. Pet. Tech.*, vol. ii., No. 7, pp. 1[illegible]7-198 (1916).

† Richardson, C., *Journ. Soc. Chem. Indust.*, vol. xvii., p. 13 (1898).

‡ Redwood, B., "A Treatise on Petroleum" (1913), vol. i., pp. 237-238; Mabery, C. F., and Dunn, O. C., *Amer. Chem. Journ.*, vol. xviii., p. 215 (1896).

a part. Such a selective putrefaction, whereby the nitrogenous portions first decomposed, the fatty materials remaining, is under certain conditions found to be proceeding in Nature; that this may actually take place would seem to be demonstrated by the last-mentioned authority having found the decomposing remains in an organic mud to contain a larger amount of fats than that of the living organisms.

It seems probable that such bacterial action, of the anærobic type, and decay in deficiency of air, possibly also associated with saline conditions, may have had an important rôle in the formation of bitumen or petroleum, and it is to be expected that such conditions would produce different results from those attending ordinary atmospheric decay.

**Micro-organic Hypothesis.**—With reference now to the smaller marine organisms (also those other than marine to a limited extent) as a probable source of origin, or what might be called the "micro-organic" hypothesis, such forms of animal and plant life, as the protozoa, diatoms, and small algæ, which exist in vast abundance and are short-lived but multiply rapidly, would certainly appear to present very suitable conditions for the purpose. Moreover, their remains are frequently associated with oil-bearing deposits, being generally present among Tertiary petroliferous series in various parts of the world, especially in the tropical regions, where they, notably those of the foraminifera, are almost invariably found. Mention in this respect may be made of the Orbitoidal limestones and marls—composed almost entirely of these foraminifera, with also some other forms, and often together with Nullipores—which are frequently found associated with the petroliferous Tertiaries, as in Borneo and Trinidad; doubtless, further investigations will reveal such beds occurring in similar conditions in other

regions. Among other examples, allusion may be made to the frequent association of the foraminiferal beds, in the middle Tertiary Series of Southern Russia, with the oil-bearing deposits; for instance at Maikop, where such beds underlie the main oil-sands; and also to the case of the foraminiferal limestone (Asmari) of the Persian Gulf area.

Further, there are the notable and suggestive conditions found in Southern California, for example, in the Coalinga district,* where the petroleum-deposits in the Lower Miocene are considered to be derived from the underlying Eocene shales, or Tejon Series, composed of an abundance of the tests of diatoms and foraminifera. These are regarded by R. Arnold as sufficient to produce more than all the petroleum contained in the oil-bearing series. It is a remarkable circumstance that the Miocene beds are only petroliferous where they overlie these diatomaceous shales, not being so where they rest unconformably on the Cretaceous, while their productivity is said to be related to the proximity of the Tejon shales.

Diatoms, as aquatic plants building up their organic material under the influence of sunlight from carbon dioxide and water, without forming starch or sugar as a product of assimilation, would appear as well adapted for forming products such as the hydrocarbons, or substances giving rise to them; moreover, included in the plasma of some species, minute globules of oil have been detected; † while G. Kramer and A. Spilker ‡ obtained from a diatomaceous ooze (seeschilck) underlying a peat-bog in the Subdivision of Uckermark, Northern Germany, a substance resembling paraffin oil, and, by

* Arnold, R., Bull. 357, *U.S. Geol. Surv.*, 1908.
† Pfitzer, in J. Hanstein's Botanishe Abhandlung, 1871, p. 33.
‡ *Ber. Deutsch. Chem. Gesell.*, vol. xxxii., p. 2940 (1899).

other treatment, a wax possessing great similarities to ozokerite. In a theory of origin from diatoms propounded by these investigators, ozokerite is supposed to be first formed, and the liquid hydrocarbons therefrom. In this connection it may be mentioned, however, that the study of the geological occurrence of natural ozokerite tends to show a reverse condition, and that this substance is evidently a residual product of the oil.

Although individually minute, the prolific abundance in which the diatoms exist at all latitudes in the sea, as well as in fresh water and marshes, is such as to provide appreciable material or sufficient sources.

A derivation has been advocated by Potonié * from the muddy slimes, or "sapropel," supposed to be formed from gelatinous algæ, occurring in association with stagnant waters, as in the case of the boghead or cannel coals, although it has been suggested that the spores of terrestrial plants, such as lycopods, may have played the principal part in the latter.

The same investigator found in the mud of the Gulf of Stettin what he considered to be a quantity of the pollen of plants, together with other organic remains, such as algæ and diatoms as well as animal fragments, and on distillation of the material obtained an oil resembling petroleum.†

Likewise, marine muds containing minute organic matter are, in various parts of the world, found to yield traces of petroleum. Siekenberger ‡ considered that petroleum was actually forming a scum on the water from organic remains in certain small saline bays in the Red Sea, while such organic muds, from which a

* *Natur. Wochenschr.*, vol. xx., p. 599 (1905).

† Potonié, H., "Zur Frage nach den Urmaterialien der Petrolea," *Jahrb. K. Preuss. Geol. Landesanst.*, xxv., pp. 342-368 (1904).

‡ *Chem. Zeitung*, vol. xv., p. 1582 (1891).

quantity of petroleum-like oil was extracted, found among coral-reefs in the Gulf of Suez, have been described by Dr. A. Wade.*

In Roumania, where there is an intimate connection between the oil-bearing Miocene and Pliocene beds and the "Salifère," which is supposed to be the seat of origin, Professor Mrazec † considers that an abundance of micro-organisms capable of living in very saline water has given rise to petroleum.

The association of salt or saline conditions with the occurrence of petroleum appears almost universal, the former substance either occurring in the solid state, or in the form of natural saline springs or the salt waters or brine occurring in the wells.

The saltness of waters found at depth may, however, be merely the not unusual condition of water existing in deep-lying strata. Thus some have endeavoured to explain the occurrence by this latter circumstance, and by the absence of conditions conducive to percolating waters and lixiviation, without attaching any great significance to the relationship.

In most petroliferous regions, however, the saline conditions are too pronounced to admit of being considered normal, their presence being manifest in the strong brines, or in the case of a markedly saline condition of the strata, often giving rise to efflorescence (for instance, in the Caspian or in some of the Caucasian regions), while considerable deposits occur in several oil-regions, too numerous or well known to need recital here. Also, the waters accompanying mud-volcanoes are generally saline; while in this respect mention may be made—as a somewhat peculiar manifestation in oil-regions—of the occurrence in the island of Tcheleken

* *Mining Magazine*, Aug. 1914.

† "L'Industrie du Pétrole en Roumanie," Bucharest (1910).

of highly saline thermal springs, often rising to the surface under considerable pressure.

It seems, therefore, apparent that the conditions of formation were generally under saline conditions, as in desiccated basins, land-locked inlets, shallow bays, or inland seas.

Conversely, natural gas and traces of petroleum are in many cases found in association with important salt-deposits, where the gas is sometimes utilized for the illumination of the mines.

It has been considered that the presence of the salt may have contributed to the process of formation, by arresting putrefaction, preserving, or modifying the decay of, the organic matter; while some have considered that it served as an active and necessary reagent in the chemical process by which petroleum resulted, or have attributed to it, as also to other associated salts besides common salt (such as the chlorides of magnesium or aluminium and bromides),* some obscure chemical action in the transformation of the original materials. It is possible, however, that the salinity may have had an effect in determining the type of bacteria employed, and thus the particular process of decomposition adapted to the formation of petroleum.

Other suggestions have been made as to a sudden advent of increased salinity in waters having effected a general destruction of animal life, thus providing a larger amount of organic materials as a source of formation. One explanation of the relationship, however, may be found in the higher specific gravity of the water, on account of the salinity, having conduced to concentration and facilitated the separation of the oil from the water. Thus accumulations would

* Ochsenius, C., *Chem. Zeitung*, vol. xv., p. 935 (1891); and *Zeitschr. Deutsch. Geol. Gesell.*, vol. xlviii., p. 239 (1896).

be more likely to occur where the conditions are saline.

But the most important significance of this association lies in the indication of the conditions attending deposition—that is, those of desiccation.

The frequent association of gypsum (or selenite)—either in the form of veins or in stratified deposits—has already been mentioned, and may also be explained by conditions of desiccation, rather than by some obscure chemical action.

Furthermore, dolomitization sometimes accompanies the occurrence of petroleum, and is likewise indicative of such conditions, although a cause for the connection is also to be found in the rendering porous of the limestones by this process, and the consequent provision of a suitable rock for containing oil.

It must be admitted, however, that the conditions found in all oil-regions are not invariably those of desiccation. In the oilfields of Borneo, for example, such saline conditions are not conspicuous, although salt-waters are found at depth; but the latter circumstance, as above noted, may not of necessity be regarded as an abnormal occurrence. Moreover, gypseous deposits are not there in evidence.

**Terrestrial Vegetation Hypothesis.**—Turning now to the terrestrial vegetation hypothesis, adherents to this mode of origin point to the association in some places, such as in Borneo, Burma, Trinidad, etc., of coal and lignite with petroleum, and to the alleged circumstance that sometimes a coal- or lignite-seam may be found to merge into one which is petroliferous.* Also, attention has been drawn by Mr. Cunningham-Craig † and by Messrs. Wall and Sawkins ‡ to the occurrence in Trinidad

* Cunningham-Craig, E. H., "Oil Finding," 1914, pp. 16-17.
† *Ibid.*, pp. 17-19. ‡ "The Geology of Trinidad," 1860.

of curious red and apparently burnt seams, termed "porcellanites," which the first-named regarded as being in a condition of transition between lignite and petroleum-bearing beds. (Although these "porcellanites," were supposed by Richardson * to be due to the disintegration of the pitch, and to consist of the mineral residue.) It does not, however, appear to be established that the condition of a coal-seam passing into an oil-bearing rock, along the identical bed, actually obtains, although they are not infrequently associated as separate beds in the same series.

Perhaps the most marked examples of the association of a coal-formation with the occurrence of petroleum are those found in Borneo, where the oil-bearing sands are intercalated in the series with numerous seams of brown coal, often of great thickness, but occurring at different horizons in independent beds, in which no passage from the one into the other is observable.

In many fields, however, in fact in the majority, no coal or lignite is found associated with the petroleum, and often the conditions under which the strata were laid down do not favour the probable proximity of large quantities of terrestrial vegetation.

In connection with this theory of origin, it should, however, be remembered that there is little or nothing to indicate that any considerable amount of terrestrial vegetation existed in early geological times, and that some of the older petroleum-deposits may, therefore, have been prior to the advent of land-plants.

While, difficulty in the terrestrial vegetation hypothesis is found in the general absence in the petroliferous beds, and frequently in the adjacent strata, of the remains of terrestrial vegetation, the hard parts of which would not be likely to disappear entirely, not even any traces

* *Journ. Soc. Chem. Indust.*, vol. xvii., p. 19 (1898).

of the original fibrous and cellulose structures being usually discernible. Moreover, cellulose on distillation would leave a carbonaceous residuum. Migration may, of course, have taken place—in the manner considered above—to overlying porous beds from the source of origin, in which case, however, the presence at the latter of beds containing indications of vegetable remains, together with some residual traces of bitumen in connection therewith, might be expected in the locality; while the close association of true bitumen with the remains of terrestrial vegetation, or coal, is not of general occurrence.

A somewhat different aspect, however, has been placed on the hypothesis of origin from terrestrial vegetation by the possibilities of the transportation of the petroleum to the places in which the beds containing it were deposited, and by researches into the behaviour of petroleum in water containing clayey sediment, and its sedimentary deposition.

As in the case of coal, in which the transportation theory of origin has served to explain some cases in which there is an absence of evidence (such as trees rooted in the under-clays, etc.) of the coal having been formed *in situ*, so, in the case of petroleum, a transportation theory of origin might explain how the hydrocarbons may have been derived from terrestrial vegetation without the series of deposits in which they are found containing evidence of the remains of land-plants.

It has frequently been noticed that oil floating down streams eventually disappears; where does it go to? It is not likely to disappear so soon by reason of evaporation.

In researches carried out on the behaviour of oil in the waters of streams, etc., by Mr. Murray Stuart * in Burma, it was found that the oil disappeared in water

* *Rec. Geol. Surv., India*, vol. xl., 1910.

containing clay-sediment. It was found that this was due to the clayey sediment having an affinity for the oil, minute particles adhering to the globules of oil, until the latter were weighed down and collected at the bottom of the water.

In this way petroleum might be deposited under water over extensive areas, such as on littoral or estuarine tracts. A change in the conditions might bring about a deposition of sand in place of the clay, and, as the weight of the overlying sand increases, the petroleum mingled with the clay would become squeezed out and absorbed in, or migrate to and permeate, the porous sand. A recurrence to the former conditions and a further change in the nature of the sediment might bring back the clay, which would then form an overlying impervious deposit sealing the petroliferous sand-bed below. Thus, a series of petroliferous beds might be formed, and if at times the source of the petroleum became temporarily stopped, some of the interstratified sand-beds would be barren; there would then be present a series of petroliferous sands, with some intercalated barren sand-beds, interstratified with clays and shales, just as occurs in Nature.

This manner of deposition of petroleum by transportation might serve to explain the occurrence of seams of coal or lignite merging into petroliferous beds, where such conditions have been supposed to occur.

This mode of deposition is not, of course, applicable only to the hypothesis of terrestrial vegetation, but also to that of marine origin, serving as a possible explanation of the way in which petroleum, whether of animal or vegetable origin, may have been deposited and permeated the beds in which it is found, before it became further concentrated by geotectonic agencies.

In this connection it may be mentioned that it has

been shown by Gottier and others that liquid hydrocarbons can be formed from marsh-gas in the presence of certain chlorides, such as rock-salt and calcium chloride; marsh-gas is, of course, a common product of vegetable origin and decomposition, and in regions covered with dense vegetation or jungle country, particularly when swampy, considerable quantities may be produced. This circumstance, if taken in conjunction with the transportation theory, would appear to present striking possibilities for accounting for the origin of some deposits of petroleum.

In connection with the oil-deposits of Egypt, Dr. W. F. Hume has suggested finely comminuted vegetable material, carried far out to sea with the finer mud, as constituting the principal source of origin.*

With reference to the possibility of oil-deposits being derived from coal, by means of natural distillation, and thus indirectly from terrestrial vegetation, an objection to a carbonaceous origin appears in the nature of the products obtained from the destructive distillation of coal, which contain a predominance of the hydrocarbons of the benzene and aromatic series, with also a considerable amount of phenolic substances; while such cannot be said to be the case with petroleum, although a minor amount of the hydrocarbons belonging to that series and small quantities of the last-mentioned compounds are usually found to be present.

In some oils, however, larger amounts of aromatic compounds have been found, notably in those obtained in Koetei, Dutch East Borneo, which apparently contain fairly large percentages; in this region, as previously mentioned, the formation affords a very pronounced example of the association of coal and oil-bearing deposits. Indeed, as pointed out by J. Kewley,† in the East

* *Journ. Inst. Pet. Tech.*, vol. vii., No. 29, p. 407 (Dec. 1921).

† *Ibid.*, No. 27, p. 209 (July, 1921).

Indies generally, the oils obtained from coal and lignite-containing formations appear to yield a higher amount of such compounds than those found in deposits in which carbonaceous beds are absent.

It is not, however, to be supposed that the derivation of the petroleum is, in these cases, to be attributed to the oal, although the latter possibly may have in some measure contributed to, and caused, the excess of such compounds in the oils.

Petroleums from South Persia and Algeria, moreover, have also been found to contain some aromatic compounds.

Occurrences of mineral resins and wax-like hydrocarbons are frequently found associated with beds of peat, lignite, and coal – such as have been termed "Dysodile," "Retinite," "Retin-asphaltum," "Neudorfite," "Mellite," etc., and a number of other names; while it is not improbable that these substances may occur, not only in macroscopic form and aggregations, but may be present also in coals in a microscopic or finely disseminated state, to some extent. In this way such substances could provide a possible source for the formation of some oil by distillation. They are of more frequent occurrence in beds of earthy brown coal, and it is accordingly possible that, in the more advanced stage of the metamorphosis of coal, they may either have become dissipated, or have impregnated the rock in a more finely divided or disseminated condition. It is possible, moreover, for the high oil-producing quality of cannel coals to be due to this cause—as also the yellow microscopic bodies (or "gels") found in such coals.

**Marine Vegetation Hypothesis.**—It now remains to consider marine vegetation as a possible source of origin, although reference has already been made to the smaller algæ, such as nullipores, as well as the diatoms, when

a derivation from marine, or aquatic, micro-organisms was being discussed.

As has been mentioned before, it is possible to produce liquid hydrocarbons from certain kinds of seaweed, and marine vegetation may consequently be regarded as providing possible raw materials for the natural production of petroleum.

Marine vegetation thrives for the most part in comparatively shallow water, or on littoral tracts, more especially between tidal limits, frequently being washed together by the waves into accumulations on the shore, and such may become covered up and buried, as in the case of the "warp" deposits, found on the east coast of England. Doubts have been raised as to whether sufficient quantities would be available, or as to whether the areas, over which the marine vegetation spread, would be sufficiently extensive to furnish adequate material for producing any considerable petroleum deposits.

It is, however, under shallow-water conditions, such as on littoral or estuarine tracts, or in basins, that petroliferous strata have most frequently been formed. Furthermore, series of strata containing petroleum often exhibit evidence of former land-surfaces, the presence of which must have been preceded and followed by extensive shallow-water conditions and shifting tidal regions; this would be more particularly significant in the case of formations containing successions of coal- and lignite-seams—as in Borneo, etc.—which indicate secular oscillations centring about the sea-level, whereby large areas must have been at the same time and on several occasions under very shallow water, and extensive tracts would of necessity have been situated between tidal limits, during the gradual transgressions and regressions of the sea, such a condition being favourable to luxuriant growths of

marine vegetation. Thus, even in the case of oil-deposits in coal- and lignite-formations, marine vegetation may not have been an improbable factor in originating some of the petroleum, and it is not inconceivable that, while the coal- and lignite-beds represent land-surfaces, some of the intermediate deposits containing petroliferous beds might represent shallow-water conditions or stretches of tidal flats harbouring an abundant marine flora. Moreover, it is also possible that the land-surfaces, covered with dense vegetation, might merge into such tidal flats or shallow water, with the accompanying marine vegetation, and consequently when the land sank, the conditions would be provided which might render possible the formation of carbonaceous seams passing into a petroliferous formation, the existence of which in some localities has sometimes been reported.

It is not improbable, moreover, that marine floras may have been more abundant in former times, and that various differing conditions may have sometimes favoured a luxuriant growth. As in the case of carbonaceous formations in regions where there is now a paucity of terrestrial vegetation, which present condition cannot be taken to suggest that there was insufficient in the past to provide for the material in the coal-seams, so, in the case of marine vegetation, it cannot be evinced that there may not have been a greater abundance in the past. In this respect it was suggested by the late Professor Vivian Lewes,* who advocated this hypothesis of origin, that the differing conditions in the composition of the sea and of the atmosphere in former times might have conduced to large growths of marine vegetation. Moreover, as was also pointed out by the same authority, very considerable quantities of marine vegetation exist in some parts of the world at the present day; while,

* Cantor Lectures, "Oil Fuel," *Journ. Soc. Arts*, vol. lxi., No. 3157 (1913).

judging from the extent of the former kelp-industry, the quantity obtainable in the British Isles was by no means inappreciable.

The advent of marine vegetation must have preceded that of terrestrial vegetation—and even that of animal life—and thus may have been the first organic appearance on the globe. The diatoms were probably among the earliest appearances, while these may at all times have constituted an important factor in the source of bitumen. It is then probable that the older deposits of petroleum have been mainly dependent on a marine vegetable origin.

Other objections which have been raised to the marine vegetation hypothesis are the absence of bromine and iodine * and the presence of sulphur in natural oils. These matters were also considered by the last-mentioned authority,† who surmised that the halogens present in the sea would have been in much smaller quantity at the time when the petroleum-deposits were formed, and the amount of bromine and iodine salts would have been very small indeed, and, in any case, the percentage taken up by the marine plants would probably have been inconsiderable. In Tertiary times, however, there may not have been so very much difference in this respect from the present. In this connection reference may be made to the iodic springs that occur in California, in association with the petroliferous Tertiaries. Also, iodine has been detected in the brines connected with seepages and mud-volcanoes in the Tertiaries of New Guinea.‡

In regard to the sulphur present in petroleum, it has been shown that sulphur is contained in certain forms

* Cunningham-Craig, E. H., "Oil Finding," 1914, pp. 23-24.
† Lewes, V., *Journ. Soc. Arts*, vol lxi., No. 3157 (1913).
‡ Wade, A., "Report on Petroleum in Papua," 1914, p. 30.

of sea-weed.* However, the sulphur contained in bitumen and petroleum varies in amount very considerably, some being comparatively free from it; while it need not be supposed that all petroleums, including those containing high percentages of sulphur, are derived from marine vegetation. Moreover, sulphur can have been introduced from extraneous sources, either contemporaneously or subsequently to the genesis of the bitumen or petroleum; or, it could be formed by the decomposition of gypsum, or iron pyrites, by organic acids, which latter mineral appears to be a probable source of the sulphur in coals.

Traces of several other inorganic substances, however, have been found existing in crude petroleum.

More recently, J. E. Hackford † has advocated, on chemical grounds, a derivation from marine vegetation, in connection with Mexican petroleum, in favour of which evidence is adduced—*e.g.*, the low nitrogen and high sulphur contents, the number of metals found in the ash obtained from the oil, and the absence of appreciable amounts of aromatic compounds.

Concerning the subject of a derivation from algæ or aquatic plants, it is of interest to note the occurrence of a deposit, in Portuguese East Africa, of a substance (termed n'hangellite, after Lake N'hangella) resembling elastic bitumen or elaterite, and yielding petroleum-like oils on distillation, the matrix of which appears to be derived from gelatinous organisms, said to consist of the blue-green algæ (Chrococcaceae), and which also contains diatoms. It has been suggested ‡ that this material may represent an intermediate stage in the conversion of aquatic vegetation into bitumen. A somewhat similar

* Lewes, V., *Journ. Soc. Arts*, vol. lxi., No. 3157 (1913). More recently, certain algæ have been found—by Messrs. Hoagland and Lieb—to contain 5 to 13 per cent. of sulphur.

† *Journ. Inst. Pet. Tech.*, vol. viii., No. 30, pp. 196 and 197 (Feb. 1922).

‡ Dalton, L. V., *Econ. Geol.*, vol. iv., No. 7, p. 618 (1909).

substance (named coörongite, and also analogous to elaterite) is found in South Australia.*

Allusion may here be made to the possible origin, in the case of some local occurrences, by means of the distillation by natural heat of oil-shales at depth, where such may be present, the hydrocarbons condensing in superincumbent porous beds; such can actually be observed to be the case where volcanic or dyke-rocks intruded among oil-shales have given rise to local occurrences of petroleum. The organic matter, known as "kerogen," which is present in oil-shale and on distillation yields fluid hydrocarbons, has been considered to be due, in some cases, to large numbers of minute gelatinous unicellular algæ, as also possibly to the spores of plants such as lycopods--conclusions which the microscopic examination of the shales seemed to confirm; in this case, then, the petroleum derived from such oil-shales would come under that of vegetable origin.† In like manner the oil-yielding cannel and boghead coals have also been supposed to be either algous, or comprising spores, in their composition and formation.

But, as has been suggested, it is possible that the oil-producing quality of cannel coals and the yellow microscopic bodies (or "gels") found in such may be due to the presence of resinous substances

In the case of the shales, however, the oil-producing property may generally originate from solid bitumens--or "asphaltic pyrobitumens"—in a finely divided state, disseminated through the rock In some cases, moreover, shales occur containing solid bitumens macroscopically apparent, or in a large enough amount in order to permit determinat on of the properties and species of bitumen

* Ibid.

† In many oil shales, however, the bituminous character is probably due to dissemination of particles of bitumen, such as "wurtzilite," "albertite," etc.

present. Thus, there are found, and have been distinguished as, "wurtzilite," "albertite," and "impsonite" shales, etc., as the case may be. While of a similar nature may be the "Torbanites." As an extreme case might be taken the "Tasmanite" shale, found near the River Mersey in Northern Tasmania, in which a bituminous substance, formerly regarded as a "dysodile,"* but analogous to albertite, occurs in relatively large grains.

In connection with processes of origin some † have distinguished a "bio-chemical" and a "dynamo-chemical" origin, in the formation of oil and gas; such taking place in the "dynamo-chemical" method under the influence of pressure and heat--more especially that due to deformation—in the same way as the production of methane in, and the loss of hydrogen from, coal—when subjected to heat or pressure.

The effect of the "dynamo-chemical" agency, while mainly conducing to the formation of gas, has been supposed to lead to the production of lighter oils—on account of condensation of the gas so produced, as well as by alteration of the pre-existing petroleum (in a similar manner as "cracking" oil under pressure); and in this way the frequent relationship of very light oils to much deformation, as also to the character and stage in the metamorphosis of associated coals, may be explained.

In this direction, some important researches have been made by D. White,‡ with reference to occurrences in North America, who has formulated a hypothesis to the effect that the grade of the oil is related to that

* Church, A., *Chem. News*, vol. vi., pp. 122-123, and *Phil. Mag.* (Edin.), vol. xxviii., pp. 405-410.

† R. H. Johnson and L. G. Huntley, "Principles of Oil and Gas Production" (1916), p. 22.

‡ "Some Relations in Origin between Coal and Petroleum," *Journ. Wash. Academy of Sc.*, vol. v., pp. 189-212 (1916)

of the coal—where both products occur—in that the heavier oils are associated with the least altered, or high-volatile, coals, and the lighter oils with the low-volatile or more metamorphosed coals—the latter having been brought to "correspondingly higher ranks" as the oil. And further, that in regions where the devolatilization of the organic deposits has passed a certain point, "marked in most provinces by 65 to 70 per cent. of fixed carbon" in the associated coals, commercial oil-pools are not found, although commercial gas-pools may occur.

Although these conclusions seem to apply in the case of certain fields in North America—*e.g.*, especially in the Appalachian and Mid-Continental regions, such cannot be said to hold good elsewhere, or be acceptable as general laws.

From such considerations it would be expected that the ratio of gas to oil in formations would be directly related to the amount of "dynamo-chemical" agency, or deformation and pressure to which they have been subjected; but such is not the case, for gas-pools, accompanied with little or no oil, occur in formations that have undergone little deformation.

**Conclusions.**—While it appears advisable to accept organic hypotheses of origin, as affording the most probable sources of derivation—in any case in respect of large deposits of petroleum—the very varied conditions under which bitumen occurs, and whereby it must have been formed in or entered into the rocks which contain it, also its diversity in type and composition, indicate the futility of confining acceptance to any single mode of origin. Indeed, some individual deposits may not have entirely originated in any single manner or from any single group of organic matter. It can be shown that under suitable conditions it is possible to produce hydrocarbons from any of the classes of raw materials

that have been mentioned, and, in the light of present knowledge, it is not desirable to discard the others for the sake of advocating one particular derivation. The possible sources of genesis may all have contributed, in a greater or less extent, to the dissemination of bitumen in the sedimentary deposits, before accumulation was effected by migration, pressure, and the advent of geotectonic movements which, combined with the action of water, brought about concentration; while the transportation theory and the data as to the behaviour and deposition of petroleum in water containing clay-sediments, may throw much light on the manner in which the petroleum originally accumulated and got into the beds in which it is found.

Whatever obscurity may be held to surround the origin of bitumen, there can be no doubt as to the source of derivation of coal, and that this is the specific substance resulting from the metamorphosis of terrestrial vegetation. But bitumen is a substance of much wider and less restricted occurrence and origin, and it is, therefore, necessary to take into consideration all possible sources; while all classes of organic matter are capable of giving rise to it.

Even an inorganic origin cannot be entirely discredited, as cases exist where some small quantities of bitumen may have arisen in this manner; for bitumen is not infrequently found contained in igneous rocks—as also graphite which may sometimes be a residual product of bitumen, and in many of such occurrences--notably in those found as inclusions in crystal cavities—it cannot be regarded as being migratory; while it has been demonstrated that petroleum is found diffused—mainly in the gaseous condition—in igneous rocks. Furthermore, even a cosmic origin may be possible, as the case of the "Kabaite" found in meteorites shows that there exists

bitumen which is not of telluric origin. But there are probably no large deposits, or supplies of any commercial value, which have inorganically originated, and the optical inactivity of the inorganic product and the environment or conditions of occurrence of petroleum, so far as the principal deposits are concerned, constitute evidence contrary to the acceptance of such a derivation.

To restrict the origin to any specific source—as to that of terrestrial vegetation—would be also restricting the conditions under which bitumen may be likely to be found.

The possibilities of an origin from micro-organisms would perhaps seem to be more generally evident, and to be the more frequently supported by available data in the field, especially in the case of the Tertiary deposits; while, as in the case of the observed occurrences mentioned earlier, conditions are to be found which would certainly appear to indicate that other or larger forms of marine organisms have given rise to the formation of petroleum. The terrestrial vegetation hypothesis, on the other hand, would seem to have less in respect of geological and chemical facts to commend it, although rendered more practicable by the possibility of the co-operation of the sedimentary transport of oil. It thus appears that the marine organic hypothesis is the most generally acceptable, and that marine organic remains have contributed the most important factor in originating petroleum, the fatty tissues having provided the principal source.*

From a synthetic point of view, however, since the sources of heat and energy contained in all combustible

* In the case, however, of animal remains, the occurrence and formation of "adipocere" would tend to indicate that even the muscle-tissues are capable, in favourable circumstances, of originating substances analogous to, or productive of, bitumen (so that the source of origin may not have been dependent merely on the fatty parts).

substances must be derived from the sun, it might be considered, at first sight, that terrestrial vegetation would appear to afford a medium better adapted for receiving and retaining solar energy than animal life or aquatic vegetation (in whose environment the intervention of water would mitigate the transmission of such influence), although the diatoms are not unfavourably situated in this respect.

But it should not be forgotten that coal is the combustible substance representing the stored potential energy directly derived by means of terrestrial vegetable organisms from the sun, and that the tissues of animals likewise possess the property of assimilating potential energy, although in this case indirectly derived (through that which they consume).

What, then, is the combustible substance arising from the burial and preservation of animal and marine organic remains? It would seem strange were no such substance formed also from marine organic remains, since accumulations of such remains—especially littoral and estuarine—are always subject to burial by sediments, and more so than the terrestrial which require, for adequate entombment, special conditions and relatively rapid terrestrial movements—or successions of such—that are not always and everywhere in operation. Besides coal, bitumen is the only other combustible substance found in the sedimentary rocks. From this, then, it would appear as very suggestive that bitumen is the combustible substance produced by animal and marine organic matter, when not subjected to ordinary subaërial decay, and when the tissues and the decomposition-products are saved from dissipation (along with the potential energy) in the gaseous form.

In this way, then, it might be expected that more bitumen should be formed than coal; and such indeed

would seem to have been the case. For, not only is the former more general in occurrence, but (in consequence of the different nature of the product, as being subject to dissipation and the provision of particular structural conditions for arresting escape) the present deposits can represent but a very fractional amount of what has been actually formed and become lost. To account for all the great quantity of petroleum that must have been originally formed, through all geological time, would demand too much from terrestrial vegetation and the conditions of submergence and burial required; especially as there is little or nothing to indicate that, in early geological ages, any considerable amount of terrestrial vegetation was in existence.

It must be considered that petroleum-deposits can seldom be indigenous to the reservoir-rocks that contain them. The latter, in the great majority of cases, consist of arenaceous deposits—or sometimes of coarser-grained material—and it is not to be expected that the conditions attending the deposition of such material would be favourable to the existence of organic life, while oil-sands are generally devoid of indications or remains of organisms. Also, it cannot be considered that petroleum or hydrocarbons of that type would be the sole product of the decomposition of the raw materials, without any other products or remains of organic matter, whereas such would seem to be the case if the accumulations of petroleum were indigenous, which would then represent a complete transformation from the original materials. Moreover, it would appear that argillaceous sedimentation is a favourable condition of formation. In cases where arenaceous deposits contain organic remains, the latter appear to have seldom been converted into bitumen. Hence, movement of the petroleum from the seat of origin to porous beds, where accumulation and con-

centration have taken place, may be considered to have been generally the case.

In regard to the conditions and process of formation from organic matter, such would consist, following the primary requirement of the rapid covering-up and burial of the materials by deposits - preferably argillaceous,* of a selective putrefaction by bacterial action under anaërobic conditions (whereby most of the nitrogenous matter would be first eliminated), and further decomposition and modification under increasing pressure, with subsequent distillation, separation, and selective migration. Possibly at some time during the process of modification a certain amount of heat may have been available, which may have been due to pressure, heat gradient, and possibly friction attending the folding movements, as well as chemical action and fermentation, and have aided in the transmutation or distillation; but time may have taken the place, in Nature, of the high temperature required for results in the laboratory. As regards postulations in respect of the various chemical changes or reactions involved in the process of formation, as have been suggested and formulated in a detailed manner by Engler, such would lie beyond the scope of a geological consideration of the subject.

The circumstance that frequently abundant organic remains exist in strata unassociated with bitumen has been regarded as inconsistent with the hypothesis of organic origin, but the formation of petroleum from organic matter would only take place under certain required conditions or factors, which may be more frequently absent than present. Moreover, the conditions contributing to the preservation or to the destruction of the hard parts of organisms may not be the same as

* In the instance, however, noted in the Mahakan Delta the sediments were partly sandy.

those effecting the conversion into bitumen or the dissipation of the soft parts. Furthermore, the petroleum may become lost by the destruction of the reservoirs, or through exposure and consequent dissipation and escape of the bitumen, the liability for such being relative to the amount of denudation and disturbance which the containing strata have undergone. Thus accumulations are seldom found in Palæozoic strata, unless they are little disturbed, as in the older formations of North America, and of Central Russia.

Finally, the required conditions or factors for the production of deposits of petroleum, originating from organic matter, may be summarized as follows :—

(1) Sufficient sources of organic matter (mainly marine and especially micro-organic) and deposition together with rapidly accumulating (preferably) argillaceous deposits, possibly in the presence of saline conditions ; or the transportation of the hydrocarbons by means of clay-sediments and subsequent deposition.

(2) The existence of a suitable medium whereby the bitumen can reach and accumulate in porous beds—either by means of capillarity and adsorption, or through cracks and fissures in the argillaceous or impervious material.

(3) The presence of such porous beds, suitable to serve as reservoirs, accessible from the seat of origin, and sealed by impervious material.

(4) The presence of water (preferably saline) in the strata, or water-logged rocks, and the advent of geotectonic conditions favourable for effecting concentration—or the occurrence of a differential porosity adequate for producing selective segregation.

The first-mentioned conditionary factors (1) and (2) are not applicable to occurrences considered to be in-

digenous, as in limestones, but probably many of such cases may be due to impregnation.

For the operation of "Dynamo-chemical" agency, in the further origin and modification of gas and oil by this process, the requisite conditions of pressure and temperature must, of course, prevail.

Lastly, it is desirable to consider that bitumen is not only of restricted or sporadic occurrence, but fairly widely and generally distributed and disseminated throughout the rocks, although it only becomes conspicuous or occurs in notable deposits where conditions favouring accumulation and concentration have obtained.

# CHAPTER III.

## THE STRATIGRAPHICAL DISTRIBUTION OF PETROLEUM, AND STRATIGRAPHICAL CONSIDERATIONS.

CONTENTS—Preliminary Observations and Practical Utility of Enquiry as to Geological Age—Prevalence in the Tertiaries and the Cretaceous—Frequent Association with Deposits of Oligo-Miocene age—Broad Stratigraphical Distribution and General Arrangement round the Globe—Considerations regarding Age of Deposits and Correlation in Different Regions or New Countries—Review of the Several Occurrences in Various Countries with reference to Geological Age—Further Observations of Stratigraphical Significance—General Characteristics of Petroliferous Strata—Summarized Table of the Main Stratigraphical Subdivisions.

ALTHOUGH geotectonic aspects are sometimes regarded as the most important in relation to accumulations of petroleum, stratigraphical observations are obviously of the utmost consequence, and it has accordingly been deemed advisable to refer to this part of the subject first.

In many regions petroliferous beds may occur with considerable constancy between definite, although generally broad, horizons, or the principal deposits may be found in the same series, and this condition may sometimes hold over extensive areas. As, for example, in the Caucasus, where, although not always occurring within identical horizons (for the beds may, of course, become terminated by lateral variation), the more important petroliferous deposits belong for the greater part to horizons of Miocene or Upper Oligocene age, while in certain areas of considerable extent the

richest deposits often lie mostly within comparatively narrow ranges. The same may be said in respect of most petroliferous provinces, in that the principal oil-bearing strata are mainly confined to a particular series or stage. It is then obvious that, in extending exploration and exploitation into fresh areas, the ascertainment of the comparative age of the beds and the investigation of the stratigraphy become of prime importance.

The actual oil-containing beds usually, of course, occur at several separate horizons in the oil-series, and rarely individually extend for great distances—as they may thin out or be terminated by variation in the lithological character or porosity, as well as ceasing to be oil-bearing on account of their structural position. In some instances, however, individual horizons may extend or be traced for considerable distances, while sometimes the same bed may again become oil-bearing where favourable conditions recur, as in the Appalachian region, where—*e.g.*, the Hundred-foot and the Berea or thirty-foot sands are of great extent; also widespread are the productive sand-beds in the Mid-Continent fields. In some regions separate petroliferous horizons may be very numerous, or, again, they may be present over a wide stratigraphical range, as, for example, in the Appalachian and Lima-Indiana fields of the United States, where petroleum has been found in strata ranging in age from the Carboniferous to the Ordovician.

Even in petroliferous areas where lateral variation is very marked, as in the case of formations deposited under estuarine or deltaic conditions, or in basins, such as are frequently associated with oil-deposits, petroliferous strata may be found at similar stratigraphical positions in separate individual basins and, in this way, repeatedly recur under such similar conditions, the separated localities of this description being sometimes distributed over wide

distances (as, *e.g.*, in Borneo, and elsewhere in the East Indies).

It may be mentioned, however, that strata containing oil-deposits are by no means invariably, or even generally, of estuarine deposition, or associated with rapid lateral variation, as has sometimes been suggested; in some cases, on the contrary (as, *e.g.*, in some of the Russian and American and Canadian regions), petroleum may occur in strata of more extended and marine deposition, where the beds may be comparatively persistent and show no rapid lateral variation—although all beds must, of course, thin out and ultimately disappear; so that well-defined and recognizable deposits or horizons may be found extending over considerable areas.

Moreover in the Cretacious of Western Canada (*e.g.*, in the regions of Alberta, and the north-western plains), there is a persistent and vastly extensive petroliferous phase within certain horizons.

Stratigraphical considerations, therefore, may be of primary consequence, and are always of much importance in oil-finding. While there is the additional necessity of stratigraphical investigation in order to ascertain structure, especially where the latter may be obscure on account of the absence of exposures or well-defined bedding in the strata, as is so frequently the case.

In this connection, however, it may be noted that usually, in most petroliferous regions, the presence or indications of petroleum are subsequently discovered in the series lower than the beds first found to contain petroleum and developed, or wherein the main or most conspicuous accumulations occur. Thus, in Trinidad, strata lower than those of the Middle Tertiary series containing the main deposits which were first developed, have subsequently proved to be oil-bearing, while on the mainland, in Venezuela, still older strata exhibit

signs of being petroliferous. Likewise, in Russia, the presence of petroleum—although in this instance extending over wide regions—has from time to time been brought to light in formations older than the Tertiaries which in the Caucasus contain the principal deposits; for example, petroliferous occurrences have been found in the Cretaceous of the Caucasian and Caspian regions, and in the Ural-Caspian area the Cretaceous, as also the Jurassic, has proved to be oil-bearing; while still farther north, in the region on the east of the Volga, petroliferous occurrences exist in the Permian (Zechstein), and also in the Carboniferous, upon which the former unconformably rests. If Northern Russia be included, oil-bearing beds of Devonian age are found in the Uchta district, and thus in European Russia petroleum is now known to exist in strata of nearly every age from Devonian upwards.

In regard to the general stratigraphical distribution, petroleum has been found in various parts of the world, in formations of practically every system or principal subdivision, and appears to have been produced at all periods of geological time, from the era of the earliest appearances of organic life on the face of the globe to the close of the Tertiary, and perhaps it may be said even until the present day. The occurrence of petroleum, however, reaches its greatest abundance in formations of Tertiary age, and appears to attain its zenith in the Miocene—especially in the lower part of that formation and at the close of the Oligocene, or somewhere about Aquitanian times. The major part—about three-fifths—of the amount of petroleum so far produced in the world is obtained from strata of Tertiary age, and the bulk of that comes from beds which are probably assignable to the Lower Miocene (most of the remainder coming from the little disturbed older strata of North America).

It is not surprising that the later formations, or the Tertiaries, should thus yield the most petroleum. Crustal movements and influences, whereby strata have become disturbed and fractured, have been in operation at all periods of the Earth's history, and since the older rocks must have been subjected to more of these disturbing influences than the formations of later origin, they are also more liable to have become disturbed and fractured, thus affording greater facilities for the escape or dissipation of the petroleum, while there has been a longer period of time for this volatilization and escape to take place. Furthermore, upward and downward movements of the Earth's crust, whereby land and sea have from time to time changed places, having repeatedly occurred, the older formations are the more likely to have been on the more frequent occasions and for a longer total period upraised above the sea, and thus exposed to denudation, by which the oil-reservoirs have been demolished and their contents allowed to become dissipated.

Thus, when petroleum does occur among older strata, it is usually found in these cases that they are comparatively undisturbed, as, for example, in the but little inclined strata of the Appalachian and Lima-Indiana petroliferous regions of the United States, in the case of the oilfields of South-Western Ontario, or in that of the nearly horizontal Permian beds of Central Russia.

In this way, then, stratigraphical considerations have a further significance, inasmuch as, if a disturbed series of strata prove to be of Palæozoic age, it is not likely that they will be favourable for productive accumulations of petroleum, while even formations of Mesozoic age, when much disturbed, rarely give good results.

So predominant is the Miocene formation (particularly the Lower Miocene, and to some extent including also

the Upper Oligocene) in respect of its association with petroleum that such might well be designated the "Petroliferous Period," and the frequent occurrence of oil-bearing strata of this age cannot be regarded as merely fortuitous. In particular, this association is most striking and frequent (especially in the Tropics) in connection with the lowest Miocene, often characterized by beds containing Lepidocycline Orbitoides,* which beds may be regarded as of Aquitanian age, and sometimes extending to the Oligocene. Perhaps the most striking instance of this affinity of petroleum for strata which are assignable to Middle Tertiary and probably Miocene age is to be found in what might be called the great petroliferous belt of the Far East. Commencing at the North, in Kamschatka, and possibly also in North-Eastern Siberia, petroliferous Miocene next appears in a belt extending along the island of Sakhalin, through Hokkaido, and down the western coast of the mainland of Japan Extending southwards through Formosa (where Aquitanian Orbitoidal beds occur), it appears again in the Philippines (where Lepidocycline Orbitoidal beds are again found) †; while there is also a reported occurrence on the other side of the China Sea in Annam. Southwards of the Philippines, petroliferous strata of Middle Tertiary or Oligo-Miocene age attain great development in Borneo—above and below the horizon of Orbitoidal (Lepidocycline) limestone—and the general line extends still farther south to Madura and Java. The same conditions are found westward, in Sumatra, while at some distance northward, formations of more or less similar age, which are oil-bearing, appear again in Burma and Assam. From Sumatra

* Often associated with the alga "*Lithothamnium*".

† Smith-Warren, D., *Econ. Geol.*, vol. iv, No. 3 (April, 1909), "The Coal Resources of the Philippine Islands," p. 229.

and Java the general trend runs eastward by Timor, and, as some occurrences in Celebes are probably also of Middle Tertiary or Miocene age, it may extend from Borneo through Celebes to Ceram, where petroliferous beds are found, and are possibly present as well in the islands of the Molucca Group. Proceeding south-eastward, the petroliferous Miocene again appears in New Guinea, while still farther south-east, similar conditions are found in the North Island of New Zealand; moreover, a few occurrences in Australia appear to be also of like age. Doubtless, further discoveries and correlations will serve to diminish the intervals and to extend the known distribution of this great petroliferous Oligo-Miocene sequence.

Curiously enough, the main trend of the great belt just described—leaving out of account Burma and Assam—follows in large part one of the great lines, or system of lines, of vulcanicity which traverse the planet.

Then, again, if the great belt of the Tropics is followed round the globe, it is also found that the known deposits of petroleum favour strata of Middle Tertiary, or Oligo-Miocene age, in a remarkable manner. Thus, commencing in the Eastern Archipelago, which contains the several and important deposits of the Dutch East Indies, and proceeding westwards along tropical latitudes, the petroleum-deposits, principally contained in strata of Miocene age, in Burma and Assam, are next noticed. Still farther west, there are the petroliferous areas of the Punjab (where oil occurs in the Miocene as well as in the Eocene) and of the region situated north of the Persian Gulf, which are not far removed from the Tropics, in both of which regions Orbitoidal (Lepidocycline) beds, probably of Aquitanian age, are found, while there are alleged occurrences on the southern and

eastern coasts of Arabia. North of the former region—if a further divergence from the Tropics is made—lies the petroliferous belt of the Caucasian and Caspian areas, in which Miocene strata figure most prominently, extending in an easterly and westerly direction, to Transcaspia on the one side, and on the other as far as the Crimea. Not much farther west, in about the same trend, this is continued again in Roumania and the Carpathians. The northern part of this latter petroliferous province, however, extends somewhat farther north to Galicia; while, at about the same latitude, petroliferous Miocene (as well as Pliocene) beds appear again in Northern Italy. Again, almost throughout Northern Switzerland, and in part of Austria, the Aquitanian beds are more or less associated with bitumen.

Returning to the Tropics, and continuing the survey in a westerly direction, there are next noticed the oil-deposits of the Red Sea or Gulf of Suez region, which are largely of Miocene age, while, on the other side of the continent of Africa, occurrences of petroleum are observable in West Africa—including the bitumen-deposits of Southern Nigeria, which, although Pliocene fossils have been found at the outcrop ("Ijebu Beds"), are probably derived from older Tertiary strata beneath. To the south in the same continent, indications are found in Portuguese West Africa (Angola), and also in Mozambique, where the Miocene Orbitoidal beds occur.

On the other side of the Atlantic Ocean, Miocene petroliferous conditions are again evident in the Caribbean region—e.g., in Barbados, Trinidad, and Venezuela (although also present at lower horizons), while the same conditions appear to extend to Colombia. In some of the districts of Mexico, oil is found in formations of like age—although to a large extent it there occurs in older

(Cretaceous) strata. Only a small transgression beyond the northern limit of the Tropics would take in the Texas and Louisiana Gulf Coastal Plain, where oil-deposits are contained in beds of the same age. Furthermore, in Peru, yet again in the tropical zone, Miocene petroliferous beds are in prominence.

It will thus be seen that practically all the well-known deposits in the regions of the Tropics are in large measure contained in strata which are probably assignable to the Miocene, or Oligo-Miocene.

In the more northern latitudes of the continents of Europe and America the principal petroliferous regions appear to comprise, for the most part, strata of Palæozoic age. Thus, in North America, there are the Lima-Indiana and Appalachian groups of fields in the United States (where the strata, although of wide range, are comprised in the Palæozoic), the Mid-Continent fields and the Canadian fields in Ontario and Quebec; while on the extreme east, in New Brunswick and Newfoundland, petroleum and gas occur respectively in the Devonian and in the Ordovician (with reported indications in the Cambrian), this last being among the oldest known occurrences. On the eastern side of the Atlantic, while the deposits in North-Western Germany—*e.g.*, those in Hanover, Brunswick, and Holstein—are principally contained in the Mesozoic (*e.g.*, in the Trias, Jurassic, and Cretaceous), petroleum is there also connected with the Permian, and there is to be noted in Central Russia an extensive area occupied by Permian strata which are frequently petroliferous, together with some occurrence in the Carboniferous; while, in Northern Russia, in the neighbourhood of Uchta, oil-bearing strata of Devonian age are found. It is not improbable, moreover, that the same conditions may prevail on the other side of the Urals, but there is as yet little definite information available concerning

Siberia, although Palæozoic occurrences are found in Northern China.

South of these Palæozoic occurrences, in both the continents of Europe and America, and north of the Tropics, Mesozoic strata are more often associated with petroliferous areas—although often in conjunction with the Tertiaries; while, in California, Tertiary petroleum extends comparatively far north, although its presence in Mesozoic beds is also known there. From what little has been ascertained regarding the occurrence of petroleum or the stratigraphical conditions thereof in Northern Asia, there is apparently a somewhat similar arrangement of predominant distribution discernible at corresponding positions, or latitudes—*e.g.*, in Ferghana Province, where petroleum is found in (presumably) Cretaceous,* also, in the case of reported indications on the Angara near Lake Baikal, in the Jurassic—although this latter locality is somewhat farther north; while there are also Mesozoic occurrences in China, to the south. It cannot be said that any such general arrangement of the predominant petroliferous conditions is also noticeable in the Southern Hemisphere.

Allusion has already been made to the Tertiary petroliferous belt of South-Eastern Europe and the Caspian region. Perhaps in this petroliferous province the deposits, principally of Miocene age, in Algeria and Tunis may also be included.

The foregoing rough generalizations, which mainly relate to the predominant occurrence and general distribution of the most noteworthy accumulations, might, of course, become modified by subsequent discoveries and revelations.

It is to be recognized, however, that difficulties and

* Although the formation there is to a large extent Eocene (Lutetian) in age. A. de Lapparent, "Traité de Geologie," vol. iii., p. 1530 (1906).

uncertainties in correlating the strata in various parts of the world, with the several subdivisions by which the sedimentary rocks of Europe are classified, must frequently arise. Thus, for example, as has been recently pointed out by Prof. Douvillé,* in the New World the Orbitoid *Orthophragmina* may occur at higher horizons than usual in Europe and the East (where it is generally characteristic of the Lower Tertiary); while it may in the Western Hemisphere be associated, in the same beds, with the Lepidocycline forms (most characteristic of the Miocene, especially the Aquitanian), cases of which have been observed (by the writer) in Trinidad. Consequently, beds which have been supposed to be Lower Tertiary may be of Miocene or Aquitanian age. Not only is it often the case that sufficient investigations have not been made, or that conclusive evidence is lacking, but there may, of course, have been contemporaneous variations in the fauna and flora in the past, just as they differ at the present day. Moreover, various authorities or investigators have not infrequently assigned the same deposits to different stratigraphical subdivisions.

It is obvious that in newly explored or little-known countries, the correlation of strata often presents great difficulties, or even impossibilities, especially where palæontological data may be scarce or not readily obtained.

Considerable difficulties of this description, for example, are encountered in Borneo, where, in certain groups of the Tertiaries in some localities, there is a great paucity of palæontological evidence (except where the Orbitoidal limestones occur), and it has sometimes become necessary to have recourse to the estimation and comparison of the amounts of hygroscopic water in the coals, in order to try and obtain a general idea of the relative ages of

* *Comptes Rendus*, vol. clxiv., p. 841 (1917).

the Tertiary formations, the coals that occur in the higher beds, as a general rule, containing a greater percentage of water than that found in those of the lower series.

Again, in some of the formations of Trinidad, palæontological evidence is scarce, or only consists of foraminifera, upon which stratigraphical conclusions have to be based. In this connection, sometimes aid to the stratigraphy, or additional evidence, can be obtained by means of the separation of the heavy residues in the sandstones, etc., and a comparison of the amounts and varieties of the heavy minerals present.

Furthermore, the possibility of the migration of petroleum, under suitable conditions, from one formation and of it permeating the porous strata of another formation, should be taken into consideration.

Consequently, the following brief review of the stratigraphical distribution of some of the better-known petroliferous localities or occurrences is given with all reserve, while it cannot, of course, approach exhaustiveness, and it is neither practicable nor desirable to classify them under less than the broadest geological subdivisions.

**Cambrian.**—Canada, British Columbia, and Western Alberta (possibly migrated), Ontario, Quebec; Newfoundland.

Gas in Oswego County, N.Y., and Alabama (U.S.A.).

**Ordovician.**—U.S.A., Appalachian and Lima-Indiana regions, Illinois, Michigan, New York, South Mid-Continent Field; Canada, Ontario, Quebec, Newfoundland.

**Silurian.**—United States, the Appalachian group of fields; Michigan, Illinois, Ohio, New York, Indiana; Canada, Ontario.

**Devonian.**—North Russia, Uchta district, Czekoslovakia (Bohemia); Canada, South-Western Ontario, New Brunswick and Quebec region, Alberta, Athabasca and Mac-

kenzie River regions, and Manitoba; United States, Appalachian group of fields, Ohio, New York, Michigan, Indiana, Illinois and Oklahoma; South America (Bolivia, etc.).

**Carboniferous.**—United States, Appalachian region, Alabama, Indiana, Illinois, Michigan, Montana, Wyoming, Mid-Continent and South Mid-Continent Fields, Texas, S.E. Utah; Nevada, and California; Canada,* New Brunswick and Quebec region; Great Britain; Holland; Germany, Westphalia, and Saxony (Pruss. Prov.); Central Russia, Volga Basin; China, Shensi and Shansi Provinces; Western Australia and Victoria.

**Permian.**—Central Russia, Volga basin; Germany, Hanover, and some occurrences in Saxony (Pruss. Prov.), Rhenish Bavaria, and Baden; Holland; Oklahoma, Mid-Continent Field, North Texas, Utah, New Mexico, etc.; S. Africa,* Orange Free State and Transvaal Province.

**Trias.**—Germany, Hanover, Brunswick, Rhenish Bavaria, and Baden; Austria; Montenegro; Spain; France, Alsace, Northern Vosges, and in the district of Ambérieu; China—*e.g.*, in the brine-district of Szechuen; Wyoming, U.S.A.; possibly in Timor; the Cape Province.*

**Jurassic.**—South America—*e.g.*, in the Argentine; Russia, Ural-Caspian region; Switzerland, in the Canton of Vaud—Vallorbes, also traces in the Cantons of Neuchâtel and Solothurn; Germany, Hanover and Brunswick, and traces in Baden and Würtemberg; Austria; Alsace, Upper Alsace, near Mulhouse, and in Lower Alsace; Portugal; U.S.A., Wyoming, Utah, etc.; Alaskan Peninsula; Somaliland; Madagascar.

**Cretaceous.**—United States, Colorado, Wyoming, Texas, Louisiana, S.W. Arkansas, Oklahoma, Kansas, Utah,

* Possibly due to the distillation of bituminous shale by igneous intrusions.

Alabama, Montana, Washington, and California; Canada, Alberta and Athabasca region; South America, Venezuela, Colombia, Ecuador, also Argentina, Bolivia, and Chile; Cuba; Santo Domingo; Trinidad; Honduras; Mexico; South-Eastern Russia, Ural-Caspian region, and some occurrences in the Caucasus; Carpathian region (including Transylvania); Central Asia, Ferghana Province; Timor; Armenia; Syria and Palestine; Egypt and Sinai; Tunis; Algeria; Yugoslavia; Istria; Austria; Germany, Hanover and Holstein; Switzerland, Val de Travers and district; Spain; Portugal; Greece.

**Eocene.**—Carpathian region; Caucasus; Armenia; Italy and Istria; Yugoslavia; Albania; Switzerland, near Basle; Bavaria; Egypt and Sinai; United States, California, Texas, Louisiana, Utah, Colorado and Wyoming; also possibly in Trinidad; South America, Venezuela, Colombia, Peru, Ecuador; while some of the lower deposits in Borneo might be of Eocene age, and possibly elsewhere in the Dutch East Indies (*e.g.*, in Sumatra); Burma; Assam; Baluchistan; North-Western India; Central Asia, Ferghana Province; Madagascar; and elsewhere in series ranging from the next.

**Oligocene.**—Caucasus; Carpathian region; Germany, Hesse; France, Upper and Lower Alsace, Limagne, Auvergne; Trinidad; Venezuela; Dutch East Indies, Borneo, etc.; and in the United States, Oregon, Texas, Louisiana, etc., and elsewhere in series extending from the next—or the Aquitanian.

**Miocene** (including Aquitanian).—Eastern Archipelago —*e.g.*, Borneo, Sumatra, Java, Timor, Ceram and the Philippines; Formosa; Japan; Sakhalin; possibly in North-Eastern China; Annam; Burma and Assam; Punjab: New Guinea; New Zealand; Australia,

Victoria and South Australia; Persia; Egypt and Sinai; Mesopotamia; Caucasus (north and south) and Caspian region; Transcaspia and Tcheleken; Carpathian region (including Transylvania); Czekoslovakia; Hungary; Yugoslavia; Austria; Germany, traces in Hesse and Wurtemberg; Italy and Sicily; France, Rhone Valley, Seyssel, etc.; Switzerland, Cantons of Vaud—Orbe, etc., Neuchâtel, Solothurn and Aargau—near Aarau, Aarburg, and Oftringen, also near Geneva—La Plaine and Dordagny; Spain; Morocco; Algeria; Tunis; Turkey; Thrace; Greece, Zante Island, etc., and mainland; possibly West Coast of Africa; Southern Nigeria; Angola; Mozambique; Trinidad; Barbados; Santo Domingo; Porto Rico; South America, Venezuela, Colombia, Peru, Chile; Costa Rica; Mexico; United States, Texas, Louisiana, Utah, Wyoming, Idaho, Oregon and California; Alaska.

These occurrences are predominantly in the Lower Miocene.

**Pliocene.**—Italy; Albania; Yugoslavia; Austria; Hungary; Roumania; Caucasus, Apscheron Peninsula, etc.; Transcaspia, Tcheleken; New Zealand; and some of the upper beds in Borneo, Sumatra, Trinidad, and Venezuela, Southern Nigeria (Ijebu): United States, Wyoming, Alabama, California, etc.*

It will be noticed from the above that a marked increase in the number of localities begins in the Cretaceous and advances to the Miocene.

(The localities mentioned under the Oligocene are not so numerous, as this is a comparatively small formation, while many of the occurrences entered under the Miocene, or Eocene, extend to beds of Oligocene age).

It would appear that the horizons in the lower part,

* The Quaternary is not mentioned, since impregnation in deposits of such age are of general occurrence in petroliferous regions.

formations of such ages are but rarely found to be associated with important occurrences or appreciable deposits, although in the Ural-Caspian region of Russia, some of the petroliferous sources lie in the Jurassic. Likewise, strata of Permian age are not frequently found to be oil-bearing, so far as known cases are concerned, with the exception of the instances in the United States of America (*e.g.*, in the Mid-Continental Field and in Northern Texas), and the occurrences in the little-disturbed Zechstein strata in Central Russia.

Likewise, series of deposits at certain horizons or minor groups in a formation are often locally found to be generally barren—or unproductive, even although superjacent and subjacent series may be oil-bearing—as, *e.g.*, in the island of Tcheleken, the lower series (Miocene) of red beds for the most part are not considerably petroliferous or productive; so that practical procedure may be based accordingly.

In the case, however, of prospecting new countries or regions not well-known, it is not always safe to predict that series of certain ages or particular groups are non-petroliferous; nor is it advisable to be prejudiced by the circumstance that formations of similar age have not elsewhere yielded oil. It is, in fact, preferable to be guided by the general character and lithological features of the deposits in the particular area.

When more knowledge concerning the stratigraphy is gained, and especially when any results or data from drilling become available, the oil-containing quality or prospects of the several series become more apparent; likewise whether any particular series or group may be associated with the more important petroliferous phase or the richest deposits, which condition, as previously noticed, is often found to prevail over regions of considerable size.

found in the region of Baku, where the quantity and concentration of the oil has sometimes been so great that comparatively thick beds of sand have become entirely saturated.

In conclusion, a reference table is given showing the main subdivisions of the stratified rocks as developed in Europe, etc., being a summary of their classification :—

TABLE SHOWING ORDER OF SUCCESSION AS APPLIED TO THE STRATIFIED ROCKS IN EUROPE, ETC.

**QUATERNARY OR POST-TERTIARY.**

**Post Glacial or Recent Epoch.**

(2) Historic—up to the present time.
(1) Prehistoric—(c) Iron, Bronze, and later Stone ages.
(b) Neolithic.
(a) Palæolithic.
(extending to the Pleistocene).

**Pleistocene or Glacial.**

Glacial and inter glacial ages in northern and southern latitudes, or at high altitudes.

**CAINOZOIC OR TERTIARY.**

**(Neogene.)**

**Pliocene.**

Newer—(b) Sicilian. (Beginning of cold age and descent of glaciers.)
(a) Astian.
Older—Plaisancian.

**Miocene.**

| | | |
|---|---|---|
| (4) Sarmatian and Pontian | (c) Pontian. | |
| | (b) Meotic. | |
| | (a) Sarmatian. | |
| (3) Vindobonian | (b) Tortonian | 2nd Mediterranean Stage. |
| | (a) Helvetian | |
| (2) Burdigalian | 1st Mediterranean Stage. | |
| (1) Aquitanian | | |

**(Palæogene or Eogene.)**

**Oligocene.**

(2) Stampian (Rupelian).
(1) Tongrian (Sannoisian).

**Eocene.**

(6) Priabonian (Ludian).
(5) Bartonian.
(4) Lutetian.
(3) Ypresian (Londinian).
(2) Sparnacian } (Landenian).
(1) Thanetian }

## MESOZOIC OR SECONDARY.

**Cretaceous.**

(Upper-Cretaceous)

(6) Montian.
(5) Danian.
(4) Aturian { Maestrichtian, Campanian } Senonian.
(3) Emscherian { Santonian, Coniacian } Senonian.
(2) Turonian.
(1) Cenomanian.

(Lower Cretaceous)

(5) Albian (sometimes placed partially or wholly in the Upper Cretaceous and as including the Upper Greensand).
(4) Aptian.
(3) Barremian (Urgonian).
(2) Neocomian.
(1) Wealden.

**Jurassic.**

**Oolitic.**

Upper Jurassic.

(5) Portlandian.
(4) Kimmeridgian.
(3) Sequanian (Corallian of Britain).
(2) Oxfordian.
(1) Callovian.

Middle Jurassic.

(3) Bathonian.
(2) Bajocian.
(1) Aalenian.

Lower Jurassic or Liassic.

(Upper) (4) Toarcian.
(Middle) (3) Charmouthian (Pliensbachian).
(Lower) (2) Sinemurian.
(1) Hettangian.

**Triassic.**

(3) Rhætian.
(2) Keuperian, "Keuper."
(1) Conchylian { (b) "Muschelkalk." (a) "Bunter."

## PALÆOZOIC OR PRIMARY.

**Permian.**

Upper. Thuringian—Zechstein } Dyas.
Middle. Punjabian—Saxonian }
Lower. Artinskian—Autunian.

*Note.*—In Russia the "Tartarian," a formation of predominantly red marls, is grouped with the Upper Permian, coming above the "Zechstein" which is very largely developed in Russia, and the latter term is there used to comprise most of the middle beds—between the "Artinsk" Series and the "Tartarian"; the "Kostroma" Series, however, may perhaps be regarded as corresponding, more or less, to the "Saxonian."

**Carboniferous.**

Upper. Stephanian—Uralian (Coal Measures).
Middle. Westphalian—Moscovian (Millstone Grit).
Lower. Dinantian—Bernician (Culm) (Carboniferous Limestone)

**Devonian and Old Red Sandstone.**

Upper. Condrusian (Famennian).
(Frasnian).
Middle. (2) (Givetian).
(1) Eifelian.
Lower. (2) Coblentzian
(1) (Gedinnian).

**Silurian (Gothlandian).**

(3) Ludlovian.
(2) Wenlockian.
(1) Valentian.

**Ordovician.**

(3) Caradocian.
(2) Llandeilian.
(1) Arenigian.

**Cambrian.**

(3) Olenidian.
(2) Paradoxidian.
(1) Olenellian.

**Pre-Cambrian** (including "Proterozoic").
**Archæan.**

# CHAPTER IV.

## THE ACCUMULATION AND CONCENTRATION OF PETROLEUM IN RELATION TO GEOTECTONIC CONDITIONS, AND THE CONSEQUENT CLASSIFICATION OF DEPOSITS.*



HITHERTO, principally broad generalizations and circumstances concerning the extended distribution of petroleum, on the grand scale, have been here considered.

It has been observed how petroliferous occurrences may be repeatedly and intermittently found over large

* It was originally intended to precede this section by an elementary description and explanation of structural features, or geotectonic conditions, but as such may lie more within the scope of a treatise on elementary geology, which can be consulted if required, it has now been omitted. (In this connection it would be well to consult "Structural and Field Geology," by James Geikie, or other text-book of this description.)

areas, or may extend over great zones or belts, but in an interrupted and discontinuous manner, although, as noted in the preceding section, the occurrences may be brought down and limited, in various regions, to more or less definite stratigraphical ranges.

It now becomes expedient to centralize further, and consider the special features of individual deposits and the conditions that are needful for local accumulations.

In this connection, it becomes, of course, primarily necessary to take into consideration the fundamental requirements for the retention of petroleum in the rocks of the Earth's crust, and the principle whereby it is possible for the mineral to become centralized or concentrated in special positions.

The first essential is evidently the presence of a porous bed, or of a rock containing interspaces suitable for holding petroleum, the protection of this reservoir by surrounding impervious rocks being also necessary in order to retain the liquid (or gaseous) hydrocarbons and preserve them from volatilization and escape.

Suitable strata for retaining petroleum, or oil-reservoir-rocks, most generally consist of sands or sandstone (or sandy shale), although sometimes composed of coarser-grained constituents, while porous limestones, especially when they have become dolomitized, also serve to provide reservoirs. Occasionally, however, petroleum is found occupying cavities and fissures, or crevices of joint-planes, as in the case of the Florence Field in Colorado, U.S.A., also in the Katalla district of Alaska, and in Mexico (*e.g.*, in the channelled limestones—Tamasopa, etc.—and fissured shales).

With reference to the principle whereby petroleum becomes centralized or concentrated, this is, of course, primarily related to the specific gravity of petroleum, in that it is usually lighter than water.

less than that of water. It may be remembered, however, that in some few cases exceptionally heavy petroleums are found, the gravities of which are as much as, or even fractionally more than, that of water; but these are usually near the surface, having become more or less inspissated. In the case of oils of such a grade, they may become mingled with the water, and not be subjected to a differential upward movement.

There are, however, other factors, besides difference in gravity, which have co-operated and probably affected or modified the separation and accumulation of oil, such as moving waters, capillarity, and the influence of gas and hydraulic pressure. It appears, moreover, that gravitational sorting of itself would often have been insufficient to overcome adhesion and friction, in cases where the porosity is low or the rock compact, and the inclination of the reservoir-roof low, as also where the oil is very viscous, but that the separation and upward movement by that means was promoted by pressure and the presence of gases, while perhaps also assisted by some motion of the oil and water. This question, however will be further considered below.

Thus, there is a prevailing tendency for petroleum in water-logged rocks to occupy the highest attainable position in the porous reservoir-rock, where its upward progress has been arrested by coming into contact with the covering of impervious rock; although, when gas is present, this would naturally occupy a higher position, thus preventing the oil from occupying the highest summit of the reservoir.

It should be further noticed that the greater the lateral expanse of the porous stratum from which the petroleum could be drained in proportion to the lateral extent of the exalted region in which the oil can accu-

mulate, the greater will be the concentration. Thus, in the case of a horizontal reservoir there cannot be so much concentration, as the oil collects and is more or less evenly distributed over the entire length of the stratum; when, however, the reservoir is inclined, the petroleum is driven to, and only collects in, the higher portion, thus bringing about concentration in the upper regions of the inclined bed.

The favourable conditions afforded by an anticlinal fold are thus evident, since the petroleum may be collected from the inclined strata on each side, to become concentrated in the region of the summit of the fold; while, a structural dome would afford still more favourable conditions for concentration, inasmuch as this would proceed from all sides towards a central point.

Let the possibilities of horizontal strata for affording facilities for accumulations of petroleum be first considered.

## (1) PETROLEUM IN HORIZONTAL STRATA.

It is obvious that, in the case of porous and petroliferous beds or reservoirs in a horizontal position, there will be a great length of stratum over which the petroleum may be distributed, should such conditions prevail over any considerable area, and the intervention of some feature effecting an interruption in the continued porosity of the bed will be necessary, in order that an enclosed reservoir may be produced. Thus, faults bringing into juxtaposition impervious rock, or a lenticular or lens-shaped form of the porous beds, or a rapid change in the lithological character and consequently in the porosity of the stratum, may bring about an interruption in the continuance of the conditions; further, deposits of

asphalt and the inspissation of the oil may seal the outcrops, where the beds have been dissected.

So long, however, as the beds are uniformly horizontal, it is evident that the conditions will not be favourable for any centralization in a limited position or for any great concentration—at least by means of gravitational separation (or without the special conditions that are necessary to produce selective segregation, as in lenses of greater porosity, to be dealt with later), and unless the beds are very highly petroliferous, and there is sufficient petroleum to accumulate in any quantity along the upper portion of the beds, considerable deposits are not likely to occur. Moreover, prevailing horizontal conditions are not so favourable to the production of any great pressure exerted by water, although, if much gas be present under suitable conditions, some pressure may be thereby provided.

In the case, however, of porous beds which are markedly lenticular or lens-shaped, conditions are more favourable to concentration, for which the region of the apex of the beds provides a suitable situation (see Fig. 1). While irregularities in the disposition of the reservoir-roof may also provide convexities, or local inclinations, suitable as positions of accumulation in horizontal strata. Petroleum occurs, for instance, under such conditions in some of the oilfields of Oklahoma, also in the Electra district of Texas, U.S.A.

Moreover, accumulations in horizontal strata may also be formed by means of segregation in portions, or lenticular patches, of greater porosity or coarser texture in the rock (as in lenses of greater porosity and "paystreaks"), in virtue of the tendency of oil to select conditions of maximum porosity, on account of its capillary power being lower than that of water. Accumulations and conditions of this nature, for instance, occur

in the Appalachian fields, Oklahoma, and Northern Texas.

Concentration might also be brought about in horizontal strata by means of progress of cementation.

Thus, as might be expected, important deposits of petroleum do not frequently occur where there is a prevailing horizontal condition of the strata—except in such cases, as just mentioned, of conditions of differential porosity, suitable for capillary segregation, being present.

Fig. 1.—"Lenticular Beds"

In the Permian strata of Central Russia, small quantities of petroleum have, in some instances, been obtained in regions where a horizontal position of the strata prevails, and in that formation thick beds impregnated with a petroleum largely inspissated to asphalt are found (Fig. 2), while similar occurrences have in a few instances been also recorded in the Carboniferous of the same region.

In the Appalachian fields, the strata are generally so little inclined that they might indeed often be regarded

as practically horizontal, but the conditions of occurrence, and the relative positions of the accumulations, are such that it is best to consider them under the heading of inclined strata. Segregation by means of differential porosity, or in more porous lenses, however, provides an important factor in these fields.

## (2) PETROLEUM-ACCUMULATIONS IN INCLINED STRATA.

When, however, the strata have become at all inclined, a different situation is created, and the petroleum is able to concentrate towards the higher limits of the porous conditions. Thus, in the case of faults bringing into juxtaposition impervious rock, the neighbourhood of the fault on the down-dip side affords the position for concentration, or, in the case of lenticular or lens-shaped beds, concentration may take place in the upper inclined extremities of the beds; and likewise, where the texture or lithological characters of a stratum change, the oil may collect on the downward side of each obstruction

It is not quite evident how much inclination of a stratum is needful in order to bring about the movement of petroleum, but this necessarily depends to a great extent on the density and viscosity of the oil—as well as on the nature and continuity of the reservoir-stratum and the texture of the rock. In some regions (*e.g.*, in the Appalachian fields of the United States of America), very slight inclinations appear to have been sufficient to cause the movement of the petroleum.

Petroleum-accumulations in inclined strata may be grouped as follows:—

(1) Accumulations due to the intervention of faults, or fault-conditions.

(2) Outcropping petroliferous beds, which have become

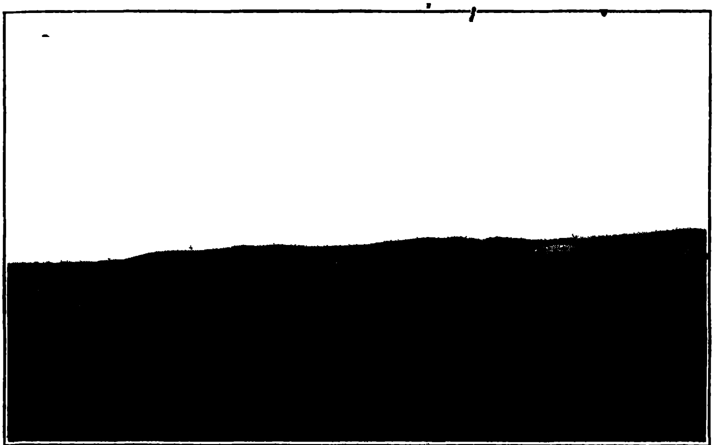
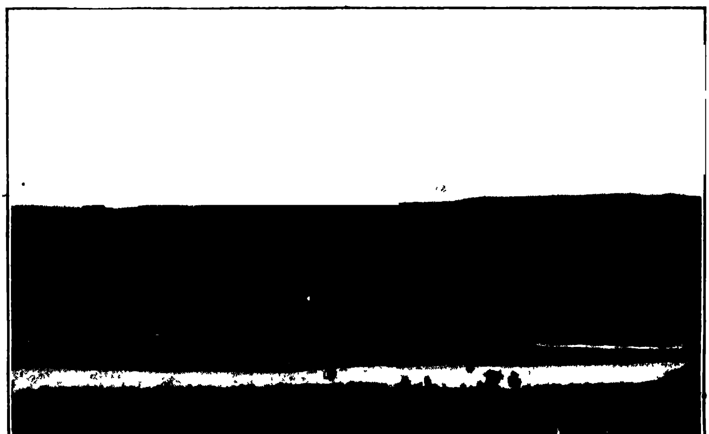


Fig. 2.—Horizontal Petroliferous Strata, in the Permian of Central Russia (*Kamischla*).



*Photos by I. A. Stigand.*

Fig. 3.—Horizontal Strata, Red Deer River, Alberta, Canada.

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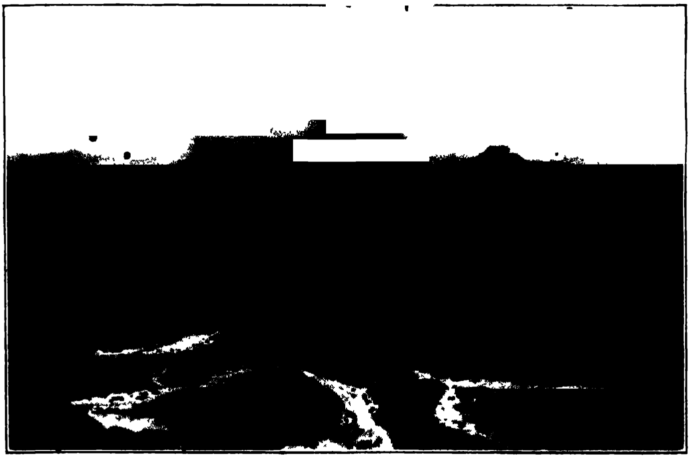
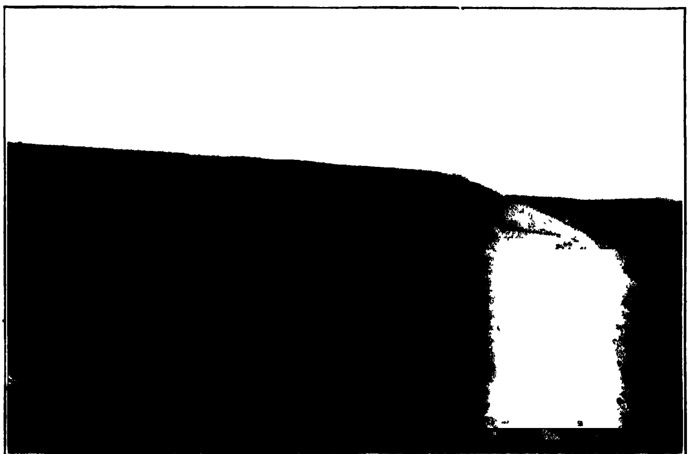


Fig. 4.—Horizontal Strata (with false-bedding), "Bad Lands," near Stevesdale, Red Deer River, Alberta, Canada.



Photos by I. A. Stigand.

Fig. 5.—Horizontal False-bedded Sandstones, with simulation of Dip, near Stevesdale, Red Deer River, Alberta, Canada.

sealed in by an inspissation of the oil, or by deposits of asphalt or ozokerite.

(3) Accumulations imprisoned by a tapering of the porous reservoir-bed, as in the case of lenticular and lens-shaped beds, or by a change in the lithological character and porosity of the stratum.

(4) Accumulations which have concentrated in variations or irregularities in dip; in this group may be included the "terrace-structures."

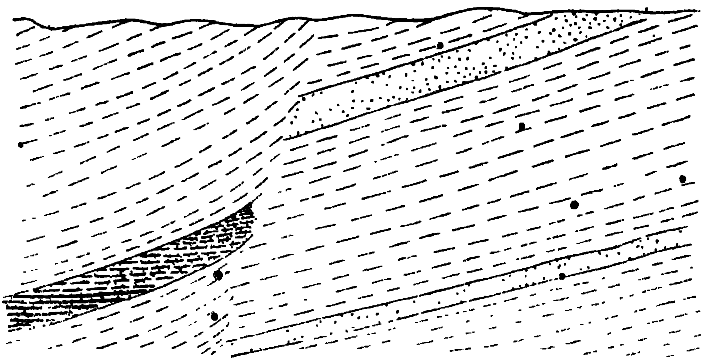


Fig. 6.—Accumulations connected with Faults.

(5) Accumulations in inclined strata abutting on unconformable junctions, and thus brought into contact with impervious strata belonging to a different formation.

(6) Accumulations in sedimentary strata where they have become interrupted by igneous and crystalline rocks.

(1) **Accumulations due to the Intervention of Faults, or Fault-Conditions.**—As might be expected, strike-faults are the most usual and suitable for bringing about the required conditions for deposits which have been originated in this way, and the accumulations are usually situated on the down-dip side of the fault (see Fig. 6).

Several oilfields and important petroliferous occurrences have originated from the influence of fault-conditions of this description, as, for instance, in some of the oilfields of California, notably in some of those of the Los Angeles district (*e.g.*, Western Coalinga), and in Mexico. More frequently, however, fault-conditions occur in co-operation with some other and more widespread or predominating influences, as that of folding, by which the general distribution of the petroleum has been effected. In such cases, they serve to modify the general distribution incidental to the wider influence, bringing about local concentration of the petroleum in sections of the larger structures; and, in addition to this influence, faults often interrupt and consequently render productive petroliferous beds which would otherwise have cropped out on the flanks of the folds and obtained free access to the surface. Such conditions are found in the oilfields of the Baku region—both at Bibi Eibat and in those of the Apscheron Peninsula—where the accumulations, while generally distributed in anticlinal or dome-shaped structures, have been much influenced and complicated by faulting. Likewise in the island of Tcheleken, where, as previously mentioned, intense faulting has taken place on the axial region of the elongated and gently dipping dome which is the predominant structure of the island, considerable modification and localization of the general distribution of the petroleum has taken place by the agency of faulting. Assuming the oil to have originally risen in the dome, it would become redistributed into smaller and more concentrated reservoirs on the advent of the faulting.

Further reference to the influence of faults on anticlines, etc., will be made when the latter come to be considered.

Although it is usually on the down-dip side of faults that productive accumulations are present, occasionally

petroliferous beds are found on both sides of a fault; but generally such an occurrence is when the strata are horizontal or only slightly inclined, as also in the case of dip-faults, or where the general distribution of the petroleum has been effected by a more widespread influence, such as that of anticlinal or dome-shaped structure. Examples of both sides of a fault being petroliferous occur in Tcheleken. In such conditions—in the case of normal (Fig. 7, *a*) inclined faults (as in the large majority

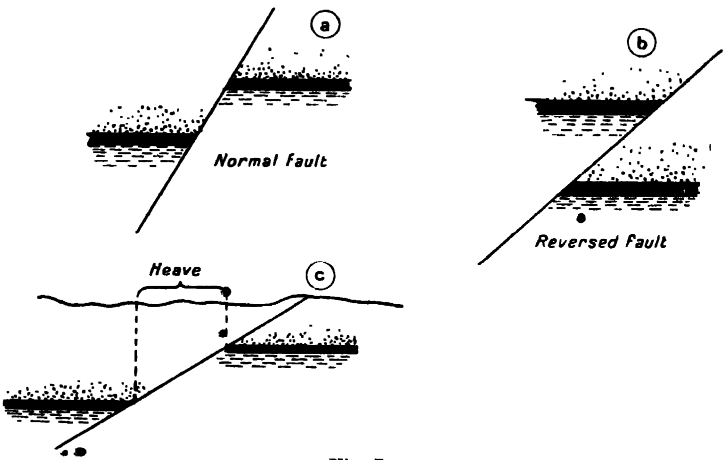



Fig. 7.

(*a*) Normal Fault. (*b*) Reversed Fault. (*c*) "Heave."

of cases), allowance has, of course, to be made for the parting and consequent local absence of the petroliferous seams within a certain margin, due to the lateral displacement, or "heave" (Fig. 7, *c*). Drilling in such barren margins has not infrequently been the cause of negative results.

In the case of oblique faults or those which diverge from the strike, the productive value will consequently vary in positions similarly situated along the fault;

since, however, faults rarely follow the strike with any approach to exactitude, the results obtained in productive zones incidental to and following faults usually are very variable.

Among other considerations bearing upon the local and often inconsistent character of results obtained in fields dependent on or modified by faulting, may be mentioned the circumstance that, where two different faults meet, three of the resulting segments may contain productive land, while one will be entirely barren. The above-mentioned considerations, together with the circumstance that the determination of the amount of hade and displacement is frequently difficult or impossible, while faults themselves are often obscure, tend to render drilling in faulted ground often of an uncertain and somewhat speculative nature, although some of the most prolific results have been connected with fault-conditions (as, *e.g.*, in Tcheleken and Baku).

Again, where a region is very much faulted or fractured, the fissures being wide or open so that there is free access to the surface, this condition may have an injurious effect on the retention of the oil-reservoirs, although the fissures, or the "fault-rock" which they contain, sometimes become impregnated with asphalt, or, in the case of the presence of petroleum of a paraffin base, with ozokerite, which process, especially in cases of the deposition of the latter substance, tends to seal the outlets and prevent further escape of the hydrocarbons. Thus, in Tcheleken the faults have become filled, or their contents of comminuted rock * impregnated with ozokerite, this circumstance having tended to influence the retention of the reservoirs.

Furthermore, clay, which has become distributed or

* Constituting the crude material known as "lep," mined for the extraction and production of ozokerite.

as by baling or pumping—and recourse may be had to this procedure in the absence of better conditions.

As might be expected, however, petroleum occurring under such conditions is not usually associated with much pressure; but it is not infrequently possible to obtain some oil by means of baling or pumping. Thus, it is generally worth while to test outcropping petroliferous beds, even in cases where no markedly favourable structure is observed—especially as the wells for this purpose are not usually required to be deep.

There is, of course, often difficulty in such cases in ascertaining the position of the water-plane, and the usual cause of failure in such trials is the location of the boring too far down-dip, and consequently water only is got. It is better, in selecting sites for trial-wells under such conditions, to err, in the first instance, on the side of commencing the well near the outcrop rather than on that of boring too far down-dip; while, at the same time, the nearer the site is to the outcrop, the less is the depth required for the boring.

(3) **Accumulations imprisoned by a Tapering of the Porous Reservoir-bed, as in the Case of Lenticular and Lens-shaped Beds, or by a Change in the Lithological Character or Texture and Porosity of the Stratum.**—The existence of petroleum in markedly lenticular and lens-shaped beds is of frequent occurrence, the beds being surrounded by impervious rock, such as shales or clays (Fig. 1); not improbably, too, the deposits may in many cases belong to this description in oilfields where the underground conditions are not readily apparent or recognizable. Among noteworthy examples may be mentioned those occurring in Louisiana and California. Also petroliferous beds of such a form are found in Trinidad.

Sometimes the apex of the beds may furnish the region of accumulation or greatest concentration; but, when the strata are much inclined, the upper extremity of the inclined beds would then provide the most favourable position for accumulation. Among examples of the inclined variety, mention may be made of those occurring in Louisiana and California.

In the same manner variations in the lithological character or texture, and consequent interruptions in the porosity of the strata, may serve to arrest the upward progress of petroleum, thus giving rise to accumulations on the down-dip side of such obstructions. In some localities very sudden and rapid lateral variations in the lithological character of beds may occur, beds of porous materials, such as sands or sandstones, rapidly changing into impervious beds, such as shales, clays, or marls.

Such a feature may sometimes have been brought about by contemporaneous erosion or irregular deposition, whereby porous beds may come to be surrounded or enclosed by impervious beds of finer constituents.

Such rapid lateral variations of pervious beds into impervious may be observed in some localities in the petroliferous Permian strata of Central Russia, where porous and petroliferous sandstones may sometimes be observed to change laterally and suddenly into impervious marls.

It is possible for the deposition of mineral matter, precipitated from aqueous solution, such as travertine and tufa, or siliceous sinter, to interrupt the porosity of beds; or the interstices or pores of pervious beds may become occupied and sealed by the infiltrated mineral matter deposited from solution, such as that of carbonate of lime.

Perhaps under this heading there might also be grouped some cases of segregation occurring in patches

of greater porosity (as in "pay-streaks") than that of the surrounding remainder of the sandy or porous stratum, the oil having been driven to occupy such positions by the superior capillary force of water, which has filled the less porous rock, as instanced in the Appalachian fields, etc. Such variations in porosity may be due to differential cementation, to coarser texture in the rock, or, in the case of limestones, to dolomitization.

(4) **Accumulations which have concentrated at Positions of Variation or Irregularities in the General Dip, amongst uniformly-inclined Strata—including "Terrace-Structure."**—In some localities petroleum is found to have accumulated at points of interruption or variation in the general continuity of dip, or at local flattenings in the inclination, such as have been denoted "terrace-structure."

The most notable examples of this mode of occurrence are found in the wide region of uniformly and gently inclined strata which extends, for a distance of over two hundred miles, across Ohio, Pennsylvania, etc., in U.S.A., on the eastern wing of the Cincinnati geanticline, where oil-pools have been found associated with positions of change in the rate of dip or with a tendency to flattening of the strata.

These accumulations mostly exist at the horizons of the Clinton and Berea Sands. Their character has been well described by Mr. F. G. Clapp.*

Two principal types of interruption in dip, accompanying the presence of the accumulations, appear to be recognizable—one consisting of a simple interruption or flattening in the general continuity of dip (which when more pronounced would merge into the "Terrace-structure"); while the other is of the nature of a lateral

* *Econ. Geol.*, vol. vi., No. 1, p. 1 (Jan.-Feb. 1911).

warping parallel to the general direction of dip of the sands, such irregularities having been called * "structural ravines," "notches," or "grooves" in the sand.

The "terrace-structures" merge into the flattenings or areas of diminution in the prevailing dip, mentioned above, or may be considered as exaggerated forms or varieties, and may be included in the same class. They have been termed "arrested anticlines" by Prof. E. Orton.†

As Mr. Clapp has pointed out, these variations may be due to a lateral pressure or a warping, and although such structures are not anticlines in relation to the horizontal, they would be of the general nature of anticlinal folds if subjected to a plane parallel to that of the general average inclination of the strata.

It is, therefore, conceivable that they may be folds produced by older movements of prior origin to that of the more widespread one by which the strata of the whole region were tilted to their present position of uniform general inclination, and that the petroleum may have formerly accumulated in the main folds at some time preceding the advent of the second more far-reaching movement. If this is the case, there thus exists a clue to the comparative age of the accumulation of the oil-deposits—at least, that relative to the incidence of the several large crustal movements which have affected the region. Also, inversely, the relative age of the two principal tectonic movements is thus ascertained by means of the positions of the petroleum.

In view, however, of the very small inclination in dip over the whole region, such anticlinal flexures must have been of very slight configuration, and it might be doubted whether they would have been sufficiently pronounced to afford appreciable conditions for concentration by

* *Ibid.* † *Geology of Ohio*, vol. vi., p. 94, 1888.

anticlinal structure and differential gravitation; while capillarity and moving water have been suggested as the principal factors in the accumulation of such deposits.

The conditions noted in the oilfields of the Appalachian region, where the inclinations of the strata seldom exceed 2°, may be described as exceptional, although undiscovered deposits under similar conditions may exist in other parts of the world, accumulations in such a mode of occurrence being characterized by a paucity of indications or exudations. Besides being connected with such structural features as those above indicated, these deposits are also associated with patches or lenticles of coarser grain and greater porosity—known as "pay-streaks."

In the Mid-Continent and other fields in North America, however, conditions of occurrence in little-inclined strata also obtain.

Examples of fields associated with the so-called "terrace-structure" occur in the Trenton Limestone of North-Western Ohio, in the Findlay field, where gas exists in an upper terrace, and oil and water are found in a lower, and in the Macksburg field, Southern Ohio; also in the oilfields of Pennsylvania, West Virginia, New York, and Kentucky; while the Wainwright field in Alberta is associated with a terrace in the general homocline.

(5) **Accumulations in Inclined Strata abutting on Unconformable Junctions.**—Such conditions of accumulation are sometimes found, the deposits usually occurring in sands dipping away from the unconformable surface of older impervious or argillaceous sediments. In such cases the petroleum may frequently have been derived from the older argillaceous deposits—although in the instance of Maikop, the accumulations would appear

to be more probably indigenous to the Tertiaries in which they occur.

One of the most marked examples of this mode of occurrence is to be found in Northern Alberta, Canada, where bituminous sands of great thickness and petroliferous deposits occur in beds, of the Cretaceous series, unconformably resting upon the Devonian shales and limestone, but in this instance the strata are nearly or practically horizontal, so that there is little opportunity for concentration of oil, or for protection from inspissation.

A notable example is also afforded by the Maikop field, in the Kuban Province of Southern Russia. In this locality a very uneven surface of the Cretaceous strata is present, on which the petroliferous Miocene series unconformably rests, and where the beds of the latter dip away from rises of the Cretaceous formation, oil has accumulated in the sands. To this condition of uneven unconformable junction of the underlying Cretaceous strata may be ascribed the uncertain results which are obtained in the borings in that field; while, when the gently inclined Miocene beds are penetrated in positions which are far from an elevation of the Cretaceous, the beds may prove to be only sparingly petroliferous or even barren.

Such marked unconformabilities as are able to afford suitable conditions for the occurrence of oil-accumulations must frequently be associated with conditions of overlap. The practical importance of this condition of overlap is readily obvious, especially in those cases in which several oil-horizons are present, where its possible occurrence must always be taken into consideration, and this has been frequently responsible for abortive wells.

(6) **Accumulations in Sedimentary Strata where they have become interrupted by Igneous and Crystalline Rocks.**—When hypabyssal rocks traverse or are intruded into inclined strata, it is evident that such may give rise to interruptions in the continuity of the reservoir, and thus afford conditions for accumulation on the down-dip-side, in a similar manner as effected by faulting.

In the northern part of the State of Vera Cruz, Mexico, the petroliferous strata are traversed by dykes or penetrated by intrusive rocks, which in some cases appear to have thus constituted factors in accumulation.

Such intrusions, however, when reaching the surface, sometimes afford facilities for escape, either at the margin or through the cracks or joints which they contain, their outcrops being marked by numerous exudations. In some instances, impervious rocks may be converted into suitable reservoirs for containing petroleum, by means of the cracking, shattering, or metamorphosis effected by the injected material.

Likewise, it is conceivable that masses or bosses of plutonic rocks may cause conditions which are favourable for accumulation, where such form interruptions in inclined sedimentary strata.

It appears that some occurrences in the provinces of Quebec and Northern Ontario, Canada, afford examples of such a mode of accumulation, while in Northern New York State,* U.S.A., gas, occurring in commercial quantities, is reported to be contained in the arkose zone of the Lower Potsdam Sandstone, where the latter is in contact with prominent knobs of granite.

* Clapp, F. G., *Econ. Geol.*, vol. v., No. 6, p. 518 (1910).

## 3. PETROLEUM IN VERTICAL STRATA.

As would appear evident, vertical or highly inclined strata cannot afford favourable conditions for the accumulation or concentration of petroleum, and deposits of importance are but rarely found under such conditions; indeed, positions where the beds dip much over 45° cannot usually be regarded as favourable, and are seldom associated with productive results. Moreover, drilling in highly inclined strata is attended with much difficulty.

In the instance, however, of the Whittier Field in California, productive results are obtained in nearly vertical beds, in the neighbourhood of faults.

It would be possible to conceive a hypothetical case of conditions whereby accumulations in vertical strata would be effected, which would be that of an inclined fault or overthrust bringing impervious rock into a superjacent position over porous and petroliferous vertical strata.

A similar condition might be brought about by unconformability, but in that case the petroleum would be liable to escape and become dissipated during the interval of time when the highly inclined beds were exposed, before being covered up.

## 4. PETROLEUM-ACCUMULATIONS DEPENDENT ON THE CURVATURE OR FOLDING OF STRATA.

Inclined strata must, of course, generally constitute parts of curves or flexures into which the strata have been folded. It is evident that these folds themselves (where intact, or respecting those portions which have not been broken or penetrated by denudation) can

furnish conditions governing the accumulation and concentration of petroleum, the more important of such folds being anticlines and domes, the influence of which in effecting accumulation and concentration—already mentioned—is too well known to need special notice here.

In order that accumulations should be determined in this manner, it is, of course, necessary that the reservoir should extend or communicate across the folds, otherwise the conditions would be merely those of accumulations in inclined strata.

Another practical effect produced by anticlinal folds is that of bringing subjacent petroliferous horizons to the position nearest from the surface, in the locality of the axes, without cropping out.

1. **Monoclines.**—Perhaps the simplest type of flexure is the monocline, although frequently connected with dislocations, and this structure may, in certain circumstances, give rise to accumulations, especially in cases where there are variations or interruptions in the porosity or texture of petroliferous beds, while the double monocline—where the flexures are opposed to or slope away from each other—may furnish a highly favourable and productive structure, as in the example of the Kampong Minyak Field,* in Sumatra.

The term "monocline" is here used to indicate the monocline proper—that is, a single flexure consisting of a local curvature or bend, in strata which are horizontal or of less inclination than that present in the curve, the beds being continued at a different level on each side (Fig. 10). It is not used here in the somewhat vague manner in which the term has come to be applied, in connection with oilfields, to uniformly inclined strata,

* Tobler, "Tijdschrift von h. Koningl. Ned. Aardrijkskundig Genootschap," 1906. Also *Trans. Inst. M. M.*, vol. xx., p. 265 (1911)

on to outcropping petroliferous beds—regardless of the circumstance that they may form parts of other structures or folds.

2. **Anticlines and Domes.**—Although by no means a necessity for the presence of productive accumulations or important fields, it may be said that anticlinal structure is usually associated with the most steady and constant results, and with the least amount of speculative element, and perhaps identified with the majority of the best fields, while also affording the simplest conditions for ascertaining the position and limits of the accumulations, and consequently the best facilities for the purpose of well-locations.

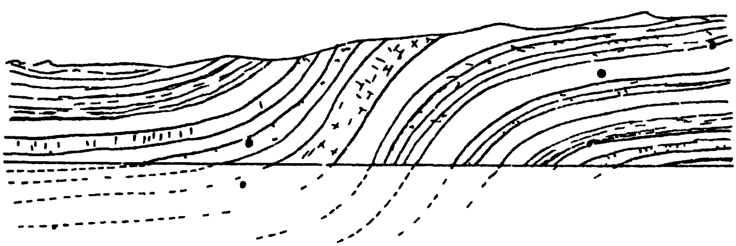


Fig. 10.—"Monocline."

Anticlinal folds, being comparatively weak structures and prone to the effects of denudation, do not often show any topographical coincidence in contour, and more frequently form valleys than otherwise, although the flanks are sometimes marked by escarpment-ridges on either side. In some cases, however, but generally in strata of younger or Tertiary age, the surface of the ground is found to show some conformity to the structure, and, as in the accompanying illustration from Japan (Fig. 11; also see Fig. 13), topographical anticlines sometimes exist. A fine example of an anticlinal

valley is that afforded by the Turner Valley in the Sheep River district of Southern Alberta, Canada, in which is situated the "Dingman Field" (Fig. 12). This lies on strata of Cretaceous age.

The flexing of strata may, of course, be of every degree of intensity and character, from almost imperceptible undulations to compressed folds, and the anticlines may be wide or gentle, narrow or strongly curved, symmetrical or asymmetrical, axially vertical or inclined at any angle, while the curvature may be slight or accentuated. For the purpose, however, of affording the conditions demanded for the concentration of petroleum by means of differential gravitation, the undulations must be sufficiently pronounced or the flexing intense enough in order to provide the requisite inclination of the reservoir, which latter may vary according to the character of the oil and the nature and porosity of the containing rock, and the consequent amount of friction and capillary attraction.

Anticlines which are nearly symmetrical, or axially vertical, with similar dips on each side, are not of frequent occurrence (see Fig. 13); usually they are more or less asymmetrical and axially inclined (see Fig. 16), in which case one side is consequently steeper than the other, while the inclination of the axis can vary or increase to such a degree that one limb of the fold may become vertical, or overhanging so as to constitute an overfold (see Fig. 17).

The symmetrical anticline with gently inclined flanks, which is usually considered or typified as the most favourable form of anticlinal flexure for petroleum, is rarely found in Nature (Fig. 13). It appears, however, that a more important consideration or feature than that of symmetry is the degree of curvature of the flexures, their acuteness or otherwise, it being generally

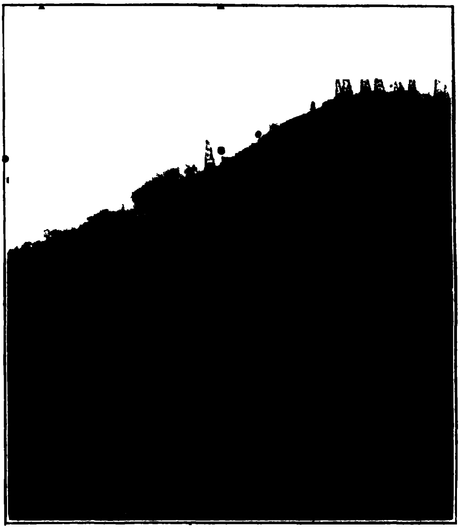


*Photo by I. A. Stigand.*

Fig. 11.—A "Topographical Anticline" (or "Anticlinal Hill"), Urase, Echigo, Japan.

*Photo by A. W. Dingman.*

Fig. 12.—Turner Valley (with the Dingman Field), S.W. Alberta, Canada.
An "Anticlinal Valley."

[*To face p.* 102.

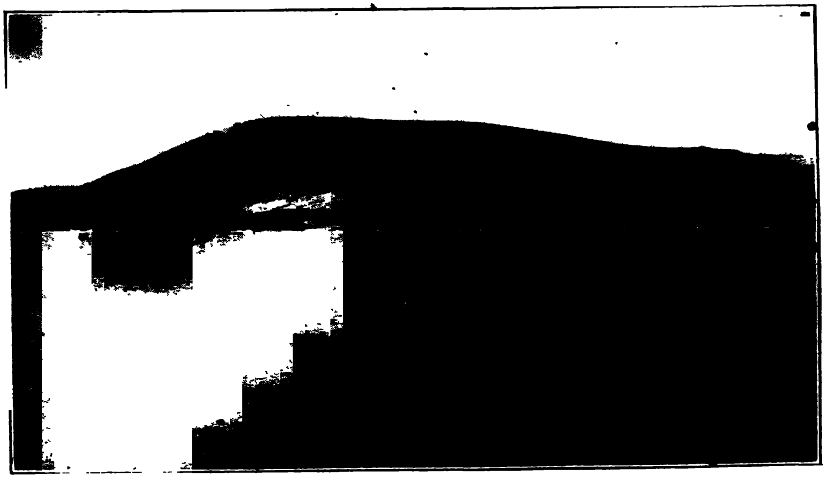


*Photo by I. A. Stigand.*

Fig. 13.—Type of almost Symmetrical Anticline, with favourable degree of Curvature (also a "Topographical Anticline").

more favourable for the folding not to be acute, or exceed a certain requisite degree of curvature.

In cases where the strata are flexed in a degree of cur-

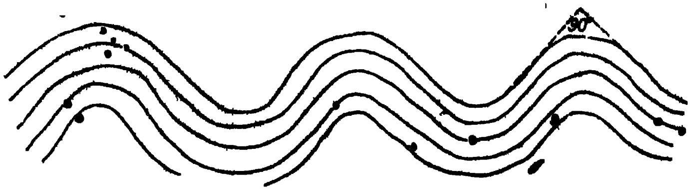
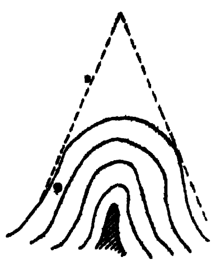



Fig 14.

vature such that no tangents to the curves make together an angle which is less than a right angle, the lines of bedding can be repeated in parallel sequence with similar curvature *ad infinitum*, for any thickness of subjacent strata.* In this case the folding is not acute (see diagram, Fig. 14).



Acute Folding

Fig. 15.

Where, on the other hand, the folding is acute, so that lines tangential to the curves of the flexures make together angles less than a right angle, the curvature of parallel subjacent strata must become smaller in radius (see diagram, Fig. 15), until, theoretically, the structure would be reduced to a central core, it being possible only for strata of a certain thickness to take their place in a particular fold. It may often be observed that the thickness of a certain folded series is greater than could be contained in such an acute fold. It is evident, then, that in the case of acute folding some sort of adjustment

* Although such folding is sometimes found to flatten gradually, and may eventually die out, with depth.

or rearrangement must be effected by disturbance, extensive faulting, or sometimes by overthrusting, although in some cases more yielding strata are present

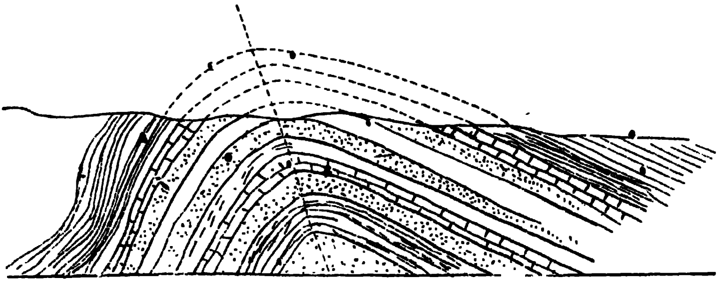


Fig. 16.—“Inclined Axial Plane.”

which would, to some extent, adapt themselves to the conditions, and it is true also that solid rocks often appear to have behaved almost like plastic bodies under the great pressures which have contorted them, in co-

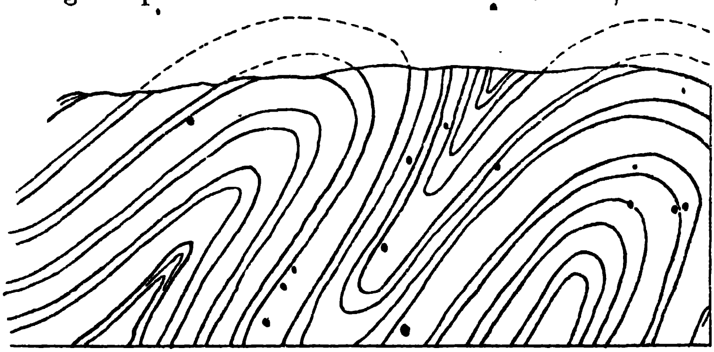


Fig. 17.—“Overfolds.”

operation, doubtless, with the downward pressure caused by the weight of vast superincumbent masses of strata; while again, the softer strata, or such as contain only thin seams of sandstone in the clay, frequently become

more acutely or highly folded than those consisting of massive and indurated sandstones or limestones.

Thus, acute folding is not so suitable for the existence of accumulations of petroleum, because the usual accompanying disturbance or fracturing did not favour the retention of the reservoirs; while the circumstance that the structure at depth may differ widely from that discernible on the surface renders the location of the accumulations and well-sites more difficult and speculative.

It thus appears that the question of symmetry and gently inclined flanks is not of such consequence as the nature of the curvature, as it is evident that a flexure may be very steep on one side and yet comply with the requisite degree of curvature—in which case it would, of course, have to be gently inclined on the other wing; some favourable flexures, for example, may be observed to be inclined at an angle of about 75° on one side and 10° on the other.

To this favourable non-acute type of folding many fields (*e.g.*, in Borneo, Burma, Southern Russia, and Japan) owe their productiveness and duration. On the other hand, the folding must be sufficiently pronounced to provide facility, or suitable inclinations, for concentration by means of gravitational sorting—although sometimes comparatively slight undulations appear to have been adequate for that purpose.

In connection with the inclination of the *apex-locus*, anticlines with inclined axial planes are often described as "asymmetrical flexures," (see Fig. 16); although in Nature such anticlines are usually asymmetrical, it is, nevertheless, apparent that symmetrical folding may also have an inclined axial plane, while there could be a hypothetical case of an asymmetrical fold with a vertical *apex-locus*. For the purpose of the location of borings in connection with anticlines of hading axial plane—

which is the usual condition, it is obviously necessary to make allowance for the deviation from the vertical of the apex-locus in accordance with the expected depth at which the oil-bearing beds may be found; the amount of such allowance may be approximately estimated by calculation,* although flexures are, of course, seldom regular, and the position is often complicated by dislocation and disturbance, as well as by the attenuation and shearing of the limbs—which is usual in sharp folding, while the axial plane, in the case of compressed folds, may not be straight, but proceed downwards in a curved line.

Non-recognition of the hade of the apex-locus, or the presence of a steeply inclined flank, in axially inclined anticlines, has frequently brought about abortive operations and the acquisition of useless land, more especially in cases where the dip of one side approaches verticality, as in the example of the Grozny Field, in the Northern Caucasus, where borings have been made and lands procured on the nearly vertical northern flank, on which no chance of reaching the petroliferous strata can exist.

Anticlinal folds must always die out, and the general manner in which they gradually disappear is by flattening out; although sometimes it may be observed that they merge into inclined strata, or are abruptly terminated by dislocation. Thus, there is practically always a gradual sinking of the axis, of greater or less intensity, the directions of strike on each side gradually becoming convergent, while the outcrops of successive beds pass over and become united in the locality of the axis (*cf.* Fig. 18).

The consequent existence of such elevated portions in anticlines is of much practical importance, the productive or most productive sectors being frequently confined

* *Cf.* Holland, Sir T., *Journ. Instit. Pet. Tech.*, vol. i. (1914).

to them; occasionally the axis may rise and fall, but such a condition is not of common occurrence, the flattening-out or sinking usually only taking place in the two directions from the summit; although it is often of intermittent intensity, thus forming local steeper declinations of the axis or giving rise to convex semi-periclines or "cupolas," which are generally very pro-

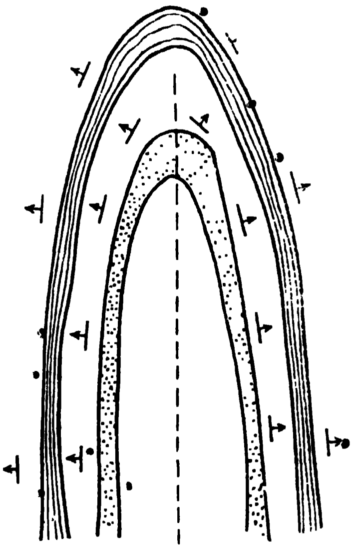


Fig. 18.—"Sinking of Anticlinal Axes." (Concurrence of strikes and uniting of the outcrops.) Diagrammatic.

ductive, as so well typified in the fields on the Sanga Sanga anticline in the maritime region of Koetei, Eastern Dutch Borneo. The longitudinal distance along which an anticline is productive is primarily dependent on the abundance of the oil and gas present, and consequently on the position of the water-limit in accordance with the amount of sinking—where the reservoir-strata are

continuous or persistent. The more depressed parts of anticlines, however, are not seldom equally productive, and this circumstance is sometimes attributable to the presence of transverse faults, which have, as it were, divided the anticline into a number of chambers; but it may be also due to the reservoirs being discontinuous or of not uniform degree of saturation, on account of the termination of, or variation in, the porosity of the oil-bearing beds, as is the most frequent condition. In some cases, such irregularities in the sinking of the axis, as above described, have afforded the positions of concentration.

In some regions the folds run for very great distances, as in Eastern Borneo, in which case the sinking is only gradual, the concurrence of the strikes of the strata on each side not being strongly marked and at first confined to the axial area; where, on the other hand, the flexure is short, the sinking is more rapid, and the structure becomes more of the nature of a pericline or dome.

Perhaps the finest examples of anticlinal folds extending for great distances, with an only gradual pitch, and of favourable form and curvature, are to be found in the region occupied by the Tertiary coal and oil-bearing series in Koetei and the Mahakan district, Eastern Dutch Borneo. The exploited anticline in the maritime region of that country is productive for a considerable distance to the south of Sanga Sanga, which locality is situated in the neighbourhood of the most elevated portion of the flexure, and is traceable for many miles farther south, only gradually sinking or flattening, as far as the coast. Likewise, on the north the fold crosses the Sanga Sanga River, where it is still highly productive, thence traversing the wide mouth of the Mahakan River, on the north side of which, at Koetei Lama, productive wells have also been obtained.

Anticlinal or synclinal flexures, although most frequently having comparatively straight, or slightly curving courses, in some cases are found to be more sinuous, while in some rarer instances they may be found to bend right round, as for example in the case of the oil-bearing anticline of the Grozny district, in Southern Russia, which turns right round to a southerly trend that is almost at right angles to the previous direction, at the same place rapidly pitching down or sinking; the same flexure is supposed to rise up again on the south side of the Terek River, where successful results have subsequently been also obtained, continuing thereafter in the more southerly course.

Not infrequently, a series of normal flexures may interosculate, anticlines commencing in the synclinal regions of the adjacent sectors before the adjoining anticlines have entirely disappeared; while sometimes the various folds in an area may not be parallel, but trend in different directions, forming a divergent and interosculating series of folds, presenting an appearance very much like that of the corrugations produced by slightly creasing a handkerchief or other thin fabric. Such series of folds may not be easy to unravel, especially when exposures are not abundant, or where the structure may have become much concealed by later or superficial accumulations. Such conditions are found in the Klias region in North-Western Borneo, in connection with the petroliferous Tertiary series, although in this case they are accompanied by disturbance and faulting.

A peculiar type of anticlinal folding is that which is sometimes called the "uplifted or open anticline," such as is found in parts of the Crimea and in Trinidad and other regions; in this case the dips increase towards and become steep on both sides in the neighbourhood of the axial region, where longitudinal faulting often

exists; while the synclines may sometimes be of a gentle dip and broad. Some folds of this description may have had bulging tops which have been entirely removed by denudation.

Such anticlines rarely give good commercial results, although not infrequently associated with prolific indications and copious exudations of petroleum. Such conditions occur in the region of Kertch, in the east of the Crimea, where sharp anticlines of this character bring up the petroliferous Lower Miocene or Oligocene, such being separated by wide synclines occupied by the gently inclined Upper Miocene or Pontian deposits. In this area numerous borings have not led to successful results (although in the case of the Tchengelek Field some results have been obtained in a flexure somewhat more favourable in form), while abundant and copious seepages are connected with the anticlines, as also mud-volcanoes which are so remarkably developed in the district of Bulganak in the north. Similar conditions may be said to extend across the mouth of the Sea of Azov, to the Taman Peninsula on the other side. In this case the general structure might be explained by the plicating movements, or lateral pressure, being prolonged after the more resisting rocks (such as the Pontian sandstones and conglomerates and Kertch limestone) had been removed by denudation from the anticlines, such strata continuing to fortify the synclines against compression similar to that effected in the anticlines.

In some instances very large and broad flexures, occupying wide regions, or geanticlines, are features associated with the occurrence of petroleum or gas, as in the great example afforded by the Cincinnati region in North America; while such often contain minor undulations or subsidiary structures which may be identified with the occurrence of the accumulations.

The wide and gently dipping anticline of the North and South Downs and Wealden area, in England, might also be called a geanticline, in which case some subsidiary flexures or undulations occur in some parts of the central area, as, for instance, in the neighbourhood of Heathfield (Sussex), etc., where natural gas has been found.

Generally the folding and successive flexures may be observed to become more compressed and axially inclined as the central region of uplift of a land-mass, or the main mountain-chain, is approached. Among oil-regions, a notable example of this condition is found in the Carpathians, where such series of folds, having their axes more or less directed towards the central chain or centre of uplift, are met with in Galicia and Roumania, the flexures becoming less compressed or inclined and

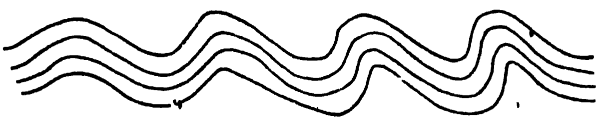


Fig. 19.—Progressiveness in Asymmetry of Parallel Folds.

more symmetrical as the plains are approached. In the same manner a remarkably progressive sequence of such different types of folds is visible in the Appalachian Mountains of North America, and strikingly illustrates a gradual increase in deformation. From more or less symmetrical flexures the folds gradually become more and more asymmetrical, until one side is sometimes nearly vertical, and the axes gradually become more inclined until the flexures become overfolds. Likewise, a progressiveness (Fig. 19) in the asymmetry and axial inclinations of anticlines is well exhibited by the succession of long parallel folds, with which the Tertiary coal and oil-bearing series are corrugated, in the eastern portion of the basin of the Mahakan River, Koetei, Eastern

Dutch Borneo; in this region the successive flexures become more axially inclined the farther westward from the coast that they are located, commencing with the exploited oil-bearing anticline of Sanga Sanga, in which the inclination of the axis and the asymmetry are not so pronounced.*

Such composite arrangements of folding as are observed in mountain-systems, as in the case of the Carpathians and the Alps, have been regarded as comprising great anticlinoria, the principal axis or crest of which would be

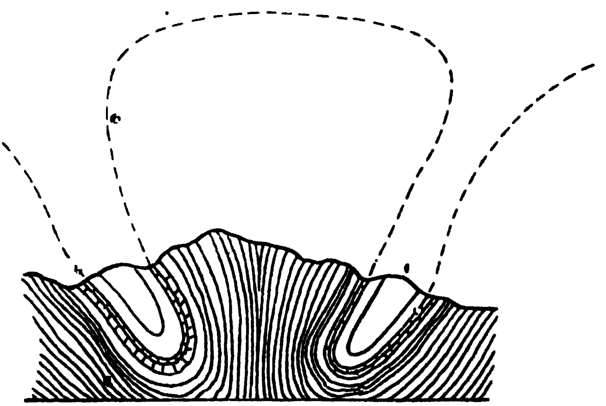


Fig. 20.—"Anticlinal Double Fold" or "Fan-shaped" Structure.

represented by the central core or crystalline mass in the main mountain-chain. A more feasible explanation, however, is that these features are due to the strata having been compressed and puckered against the great central core of schists or protogene.

In some oil-regions, however, structures resembling true anticlinoria—on a smaller scale than in the cases just mentioned—are found, more frequently in the areas containing the more yielding or argillaceous strata. Thus, in some areas of Trinidad occupied by the Naparima

Clays, such systems of folds, subordinate to one predominating uplift or bulge of sufficient intensity to keep that stratigraphical formation on the surface over the greater part of the area concerned, are sometimes noted. Likewise, in Barbados, although on a still smaller scale and not entirely confined to the softer or argillaceous deposits, such a description of folding is occasionally discernible in the highly folded strata of the petroliferous Tertiary ("Scotland") series.

**Domes.**—There may, of course, be all gradations from a pitching anticline to elongated domes or periclinal structures, but complete or symmetrical domes are of rare or unusual occurrence, although modified structures of this description are sometimes caused by the transverse meeting of two flexures, or series of movements and compression in different directions. Examples of such elongated dome-like structures are found in Trinidad, as in the field of Fyzabad, where two such irregular domes, not in alignment as to their axes, comprise the principal areas of production. In regard to other descriptions of domes, allusion may be made to the dome-like bulges sometimes produced by igneous intrusions and laccoliths, in overlying sedimentary strata, although there do not appear to be known examples of any such being connected with oil-accumulations; those formerly supposed to have thus originated in the oilfields of Mexico being most probably of prior formation to the intrusives which appear to have been subsequent to the production of the salient geotectonic features.* Further, there is the particular type of the saline dome, as exemplified in Texas and Mexico (Isthmus of Tehuantepec), and also found in Roumania and Algeria, etc., which has often produced prolific

* Stewart, P. C. A., *Journ. Inst. P. T.*, vol. ii., pt. 5, p. 11 (Dec. 1915).

results. Numerous hypotheses have been advanced in explanation of the origin of saline domes, and the literature concerning them is so abundant that it is not necessary to deal with the subject here.* It seems, however, most probable that they are the result of the action of geotectonic forces on the plastic saline masses with which they are connected, along lines of weakness or possibly dislocation, in a similar manner to the more exaggerated cases found in the Carpathians, where the "Salifère" has sometimes been thrust through the overlying strata, giving rise to the "diaper-structure" of Mrazec.† Other hypotheses explaining the origin of these domes are that they have been caused by growth due to the crystallization and consequent expansion of the salts, and also that the latter were deposited by mineral springs contemporaneously with the surrounding sediments.

The occurrence of such saline domes is being found to be far more widely distributed than was generally supposed.

3. **Petroleum in Synclines.**—It seems doubtful that any typical examples of synclinal accumulation actually exist, although oil may be found in minor synclines, subsidiary to some dominating structure, where the petroleum is sufficiently abundant to fill them, or likewise where some independent feature may have given rise to accumulation. As has been pointed out, if the rocks are dry, oil would tend to sink downward in the reservoir-bed and accumulate at the bottoms of the synclines; but the actual occurrence of such cases is questionable, although sometimes supposed to exist,

* A discussion and bibliography is contained in a paper by Sherburne Rogers, G., *Econ. Geol.*, vol. xiii., No. 6 (Sept. 1918).
† Mrazec, L., *Bull. Soc. Sci.*, Bucarest (1906).

while the presence of water is necessary in order to promote concentration and effect accumulation. Such conditions have occasionally been reported as found in connection with some pools in the Appalachian fields, but then only respecting minor synclines or subsidiary structures, while often water has been subsequently found farther down dip.

In the instance of the San Juan * field in South-Eastern Utah, which is situated in a semi-arid region, it is supposed that there is little water in the formations, and that oil should be present on the flanks of the broad syncline which underlies part of the district.

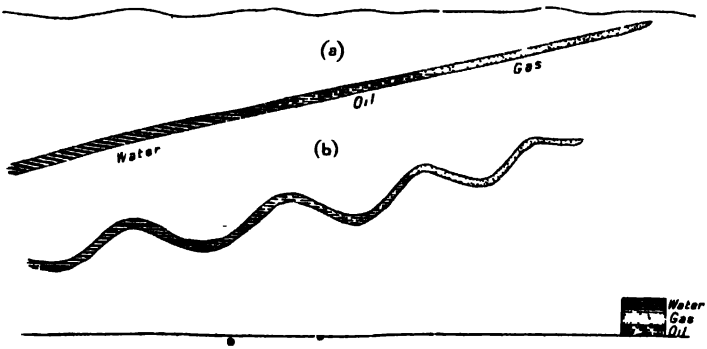



Fig. 21.—Disposition of Accumulations and Subsequent Folding. (*a*) Before and (*b*) After advent of the folding.

Moreover, the strata for some depth in synclines would come to the surface and crop out, and water would be thus admitted to the porous beds.

Another way whereby oil might come to be present in synclines could occur when some accumulation might have already taken place by means of a prior influence, before the advent of the predominant folding; as, for instance, in the case of the reservoir having previously

* Woodruff, E. G., *U.S. G. S. Bull.* 471 (1912).

been sufficiently tilted or inclined so as to have produced gravitational sorting, the oil might remain in those synclines, as well as the anticlines, formed in the region of the reservoir formerly occupied by it (see Fig. 21). Clear examples of such a condition, however, do not appear to be forthcoming or known, while it is, moreover, likely that some percolation of water from above would take place, which would ultimately find its way to the synclinal trough.

In the case of the occurrence of a very heavy oil, of about the same density as water, such might be present, to a certain extent, associated with the water in the synclines, although petroleum of such a character, being generally due to inspissation, is usually found near the outcrops.

In the conditions of reservoirs of limited extent, or interruptions and variations in the porosity of horizons, deposits might occur on the flanks of synclines, but such would come under accumulations in inclined strata, which have already been considered.

## 5. ACCUMULATIONS IN HIGHLY FOLDED OR DISTURBED STRATA.

Strata may, of course, have been more intensely influenced by crustal compression and plicating movements, so as to have become convoluted or contorted, and much dislocated, while sometimes forming a complex system of minor folds and crumplings difficult to unravel. It is evident, however, that such structure cannot be regarded as favourable for the accumulation or retention of oil, while such conditions must present much speculativeness for drilling.

As might be expected, then, highly folded and disturbed strata are not frequently associated with important

deposits of petroleum, instances of such occurrences under these conditions being practically confined to the Tertiaries, and but rarely found in strata of pre-Tertiary age, while it may be said that no such examples are known in the Palæozoic.

Perhaps the most important examples of deposits of petroleum associated with disturbed formations are those found in the Carpathians, where, in the regions near the centre of the uplift, the oil-bearing strata have been sharply folded, much dislocated and often overthrust, while so great has been the lateral pressure that the Miocene Salifère has sometimes been thrust up so as to pierce the overlying deposits, as in that which has been termed "diaper"-structure by Mrazec. Likewise, in California, fields exist where disturbed and complicated conditions of structure obtain—as, *e.g.*, the M'Kittrick Field and others; such have been fully described in an extensive literature, and thus will not require further allusion here.

In the Maidan-i-Naftun oilfield,* in Southern Persia, disturbed structure and compressed folding is found in connection with the oil-bearing flexure, which sometimes becomes isoclinal and accompanied by overthrusting, also passing into fan-structure; although some portions, among them the most productive, appear to be more of the nature of a comparatively regular anticline.

In Trinidad many of the fields are associated with conditions of disturbance or great plication, but in some of the more disturbed areas (*e.g.*, the Tabaquite Field) exploitation is only successful on account of the high grade of the oil which is obtained. The petroliferous Tertiary series in Barbados has been subjected to intense

* Busk, H. G., and Mayo, H. T., *Journ. Inst. P. T.*, vol. v., No. 17 (Dec. 1918).

plication, often of an almost convoluted description, with fan-structure on a small scale sometimes observable, the structure resembling that of a miniature mountain-system; while, up to the present time, drilling has hardly been there attended with commercial results, although a small output has been obtained from some of the borings at Turner's Hall. Likewise, in British North Borneo, the petroliferous Tertiary series on the west coast is much disturbed and folded, so that borings there have not been successful.

In some instances disturbed and highly folded conditions may obtain in some parts of a region, or over the greater portion of it, while in other parts, areas of comparatively little disturbance or plication may be found, where the strata have not been much affected. This may be due (where various descriptions of deposits occur) to a differential folding in strata of different consistency and resistance; thus clays or soft shales, and thin seams of sandstones, would be likely to yield more to the disturbing influences than massive or indurated sandstones, conglomerates, or limestones.

For example in Trinidad, where the Tertiary deposits are generally much disturbed, such areas of comparatively less disturbance and simpler folding, or even of little-inclined beds, are to be found; but the formations composed of clayey strata and softer deposits, or of a predominance of such, generally prove to have become the more intensely folded or more complicated in structure.

In some fields the strata appear to be more disturbed and folded at the surface than at a great depth, as shown by data obtained from the logs of borings.* This would certainly seem to be the case in respect of some fields in Trinidad, while similar conditions have been observed

* While, in some cases, folding appears gradually to die out with depth.

by Dr. A. Wade * in Papua (*e.g.*, on the field of Upoia, and also at Orevi), although in the latter case he has attributed the cause to undermining and the removal of softer sediments below by the action of underground waters and the consequent collapse, or settling down, of the overlying strata. Such conditions, however, could be brought about by differential folding in different characters of rocks or deposits (as considered above), although the nature of the deposits does not always quite serve to meet the case in the examples noted. But this feature could be also explained, where the movements and folding were of late or recent occurrence—or are still in progress, as due to the formations having become more disturbed, by the movements, at or near the surface than at depth, denudation not having accomplished the removal of the more disturbed zone; for it is likely that the superficial deposits would yield more readily to the movements, or would be more susceptible to disturbing influences, than those supporting the weight of masses of superincumbent strata.

It is sometimes supposed that the association or proximity of vulcanicity is connected with an unfavourable or disturbing influence. The reverse, however, seems often to be the case. Not only does volcanic action appear to have generally intersected the sedimentary rocks with the production of little or no disturbance, but it is often observable that the strata are little disturbed in the neighbourhood of localities of volcanic activity in regions where elsewhere they may be highly disturbed or folded. Thus, in Java, the volcanoes appear to have cut through the sedimentary formations without disturbing them in the environs of the former, fragments of the Tertiary strata being often found amongst the volcanic ejectmenta—for example, on the active volcano

* Report on Petroleum in Papua, 1914, pp. 9-11.

of the Papandaijan pieces of the Tertiary "Kalkstein" are strewn around the summit, while favourable conditions for the occurrence of oilfields occur in the Tertiaries not far from the volcanic mountains. In British North Borneo, where disturbed conditions of the Tertiary strata generally prevail, particularly on the west side, the Tertiaries on the east side, in the region of the Dutch boundary and Sibuko Bay, wherein andesites occur and volcanic action of a subsequent period has taken place in the neighbourhood of Tawao, are little disturbed. The same conditions are noticeable in the West Indies, the Tertiaries in Trinidad and Barbados being much disturbed and folded, while in Antigua, the western portion of which is composed of volcanic rocks, and in other of the Leeward islands lying in the belt of vulcanicity, the Tertiary strata have been little disturbed.

Further, there is the well-known instance in Mexico, of volcanic action having been associated with, and intrusives actually traversing, the oil-bearing formation, while somewhat similar conditions obtain in Japan.

# CHAPTER V.

## PROBLEMS AND FACTORS IN THE MOVEMENT AND ACCUMULATION OF PETROLEUM.

CONTENTS—Gravitational Sorting—Capillary Action and other Factors influencing Concentration or Segregation—Difference in Gravity Hypothesis or the "Anticlinal Theory," and the Question as to its Adequacy—Gravitational Separation of Oil from Water in Sands, etc.—Hydraulic Pressure in Reservoirs and the Occurrence of Gas and Motion of the Fluids in the Rocks (as promoting separation)—"Induced Porosity" and Cavities and Fissures in Rocks, and the Separation facilitated thereby—Capillarity, Differential Porosity, and Selective Segregation—The "Hydraulic Theory," etc.—The Respective Rôles of the Factors in Concentration—The Pressures connected with Oil- and Gas-Accumulations—Their Causes and Effects—Presence of Water a Factor required for Concentration—Relation of Deposits to Large Tectonic Basins.

It is seen that in most cases the various foregoing classes of structure, which are identified with deposits of petroleum and have been exemplified by actual occurrences in nature, are connected with the principle that the accumulations occur at the upward termination of the reservoirs, or in the most elevated part that is unoccupied by gas—when present.

Accumulations would thus appear to be generally dependent on difference in gravity, or "gravitational sorting," for concentration into such positions.

It is, however, probable that other factors (as already noticed) have contributed to and influenced or modified the movement and concentration of the oil, such as, *e.g.*, moving or percolating waters, capillary action, and varying porosity, as also hydraulic pressure and the

action of gas, and that in some cases difference in gravity unaided by such would not be capable of completing the movement and collection of the oil into accumulations, or provide sufficient force to oppose the resisting influences encountered in the rocks or deposits. While in some cases, as when the inclinations of the beds are low (*e.g.*, in the Appalachian Fields, where the dips do not often exceed 2°), such factors may have provided the more important agency in concentration—although in that instance the accumulations seem often to conform largely to broad structural features.

The hypothesis based on difference in gravity has, indeed, been sometimes disclaimed or criticized as being generally incapable of accounting for the movement and separation of oil in the porous rock, the upward hydrostatic force thereby exerted on the oil having been considered as insufficient to overcome such opposing forces as adhesion, friction, and capillary interference, which would be encountered in the rocks. Thus, the adequacy of this hypothesis—sometimes called the "anticlinal" theory— has, for example, been questioned by M. J. Munn,* although mainly in consideration of the exceptional conditions found in the Appalachian Fields (with especial reference to those observed in the Sewickley Quadrangle). This authority has mentioned molecular repulsion of oil and water, capillary adhesion, interstitial molecular cohesion (which is proportional to the viscosity of the oil), and both static and kinetic friction, as forces acting in opposition to the movement of oil in water. It is probable, however, that only the three last-named are of much importance.

The hydrostatic force exerted on oil in upward direction may be usually taken as being equivalent to about 30 per cent. of the weight of the oil, in the case of an

* *Econ. Geol.*, vol iv., No. 2 (March, 1909).

average oil—of a specific gravity of about 0·8, in saline water slightly denser than pure water—as, *e.g.*, in the instance of the oil and water found in the Hundred-foot-Sand, the specific gravities of which are about ·7977 and 1·06 respectively.

Now, while gravitational separation does not readily take place in fine sands, and not at all in sands or other media of less than a certain critical degree of porosity, it appears that such separation of the oil is effected in sands or other media of comparatively large-sized grain or pore-space—*i.e.*, within certain limits of porosity. That this is the case can be experimentally demonstrated, although the process may be gradual and require time (under static conditions), and not always be readily or completely brought about; but this is largely due, when in experiment the materials are confined in enclosing vessels, to obstruction of the necessary displacement of air—as well as to the capillary interference.

It can be further experimentally shown that gravitational separation can be promoted by water-pressure from below, likewise by passing air through the sand, and when, moreover, the separation has been started by this latter method, it generally afterwards continues with more or less readiness. This latter circumstance may probably be due to the formation of minute channels, or passages for movement, through the sand.

Gravitational sorting is further promoted by any motion of the liquids, such tending to overcome capillary interference.

Now, in nature, it is probable that the presence of all the influences aiding gravitational separation, such as those just noted, is to be found.

Thus, as regards hydraulic pressure, this appears to be most generally present in connection with or around oil-pools. That this is the case would seem to be evidenced

by the circumstance—as previously observed—that oil-flows frequently give place to water, which encroaches in the reservoirs on exhaustion, and that sometimes production from wells is found to increase after high rainfalls, also that flowing water-wells are frequently encountered on anticlines—or in connection with other structural conditions of similar influence; while the rise of the oil in flowing wells is probably largely due to this cause, in conjunction with the pressure of gas—although the latter alone can also raise the liquid. The existence of such hydraulic pressure in anticlinal folds has sometimes been questioned, on account of higher drainage-areas being apparently unavailable. Not only, however, are adjacent folds not infrequently of higher pitch, thus bringing the reservoir or the porous beds—in the case of such being continuous—to a higher elevation therein, and consequently providing a "water-head," but a certain amount of percolation of water from above generally takes place—as through faults, fractures, joints, or other fissures and means of communication with the surface, and in this manner the necessary weight of water for giving rise to hydraulic pressure in the reservoirs would be provided; this is assuming that such facility for ingress of water has access to, or the weight of this water is mainly distributed over, the less elevated parts of the reservoir or those not containing oil and gas—as would appear to be generally the case. Even supposing, however, that water had access also to the elevated portion of the reservoir that contained oil and gas (these not being able to escape easily), the pressure created by the column operating in, or from the direction of, that region of the reservoir would not be so great as that acting on the inferior or water-containing parts, since a portion of the former column would be occupied by oil and gas. If oil and gas were absent, probably also hydraulic pres-

sure would often be absent in anticlines or in the upper regions of the reservoirs, the water not reaching the summit.

In some fields, however, exhaustion of the petroleum does not appear to be accompanied by any encroachment of water in the wells, but this may be due to the hydraulic pressure having found equilibrium, before the water had risen to the level of that part of the reservoir which is at the position of the wells—on the removal of the gas and oil.

This circumstance, as well as variations in pressures and in the levels of the static heads of the water in different wells within the limits of certain fields, has been regarded as inconsistent with the hydraulic theory of pressure.* But such variations may obviously be affected by varying conditions of porosity and means of communication through the rocks, as also by facility of access from other areas or local interruptions in such, and finally by the amount of gas formed or present.

It is not, however, intended to suggest that gas is not also an important factor in causing pressure or in raising oil in the case of spouters—especially when occluded in a supersaturated state in the oil.

In the case of arid regions and conditions of the rocks not being fully water-logged, such water-pressure must, of course, be frequently absent.

In some instances water under pressure, of deep-seated or thermal origin, may be present, as, *e.g.*, in Tcheleken, where hot saline springs under considerable pressure are associated with the oil-deposits.

Likewise gas, either generated from the oil—as of dynamo-chemical origin, or derived from other or lower sources, and the transmission of it through the reservoir-

* Thompson, A. B., "Oil-Field Development," 1910, pp. 131 and 132.

rocks, is not unlikely to be present, and to promote the separation in the manner above indicated.

In another way, gas transmitted through the fluid may bring about some separation and accumulation, by carrying up oil as envelopes of bubbles.

Furthermore, some motion or flow of the oil and water may not improbably take place in the reservoirs —this also giving aid to gravitational separation. Although oil-deposits often appear as though hermetically sealed until penetrated by the drill, that some degree of circulation or escape is often taking place is shown by the usual occurrence of seepages or exudations of oil and emanations of gas, the pressure of water gradually forcing out the oil.* Moreover, there is probably from time to time some rise and fall of the water-level in the reservoirs, due to variations in the amount of meteoric water or in rainfall, as also to the formation of more dynamo-chemical gas at the summit of the reservoir. In this manner some motion would be provided conducive to gravitational separation—as by overcoming capillary interference. While also the oil—in an emulsion of the fluids—would tend to become left behind in the sand as the water fell, thus being also separated in this manner.

An important circumstance, however, facilitating gravitational separation, is the probable presence in the reservoir-rocks of super-capillary interspaces other and larger than interstitial, such as fissures, fractures, joints, cracks, cavities and other openings, within which gravitational separation would be able to take place unrestricted and unimpeded, and not be affected by capillary interference. Such super-capillary openings would be chiefly due to "induced porosity," † which is probably

* Such escapes sometimes appear to increase when the rainfall is high, which circumstance would tend to indicate that this is often the cause.

† Lauer, A. W., *Econ. Geol.*, vol. xii., No. 5, p. 436 (Aug. 1917).

of greater importance and more frequent occurrence than is generally suspected, including such openings as those arising from folding, as also fissures, cracks, etc., formed by rupturing or otherwise, and bedding-partings and joints, and sometimes also those due to brecciation. In the case of loosely consolidated sands, the conditions for the occurrence of such induced porosity are not so suitable, although it is probable that, even in loose sands, there are a certain number of openings, such as may be due to folding, cracks, and cavities—the last-named being liable to arise during any "settling-down" of the sand, especially when partially coherent or cemented. In some cases the yield from certain oil-sands or reservoir-rocks has been greater than their interstitial porosity might be expected to be capable of retaining, but it is probable that this is due to such induced porosity.

The rôle played by capillarity in accumulation would be principally that of modifying the concentration and accumulation of the oil in the deposits by selective segregation in conditions of varying porosity, in virtue of the tendency of water (the capillary power of which is about three times that of oil) to seek the conditions of maximum capillarity, the oil being relegated to those of maximum porosity. In this way also, the petroleum would tend to accumulate in any fissures or cavities that may be present.

In cases of the occurrence of conditions which do not give scope to concentration into deposits by means of gravitational sorting, such selective segregation by capillary action may play the principal part or independently produce accumulation, as in the case of deposits in patches or lenses of greater porosity, associated with horizontal or but slightly inclined strata.

There has, indeed, been proposed a hypothesis, as

formulated by C. W. Washburne,* which is mainly based on such capillary action and selective segregation for the general explanation of oil-accumulation and separation.

The efficacy of such differential or selective capillary action in separating oil and water can be experimentally illustrated by introducing two plates, placed together but slightly parted on one side, into an emulsion of oil and water (mixed by agitation), when it is found that the water fills the narrower part of the interspace, the oil occupying the wider portion. Again, when a finely porous rock, or other material, is placed in such an emulsion, the water alone is absorbed, the proportion of oil in the mixture thus becoming increased.

On account of the difference between the surface-tensions of oil and water becoming less with increase in temperature, until they reach equality, the influence of such differential and selective capillarity should decrease with depth, ultimately altogether ceasing to be effective, to which condition increase in pressure would also contribute. The depth within which such action would be limited has been opined to be about 3,000 feet.†

In regard to another possible cause of separation or accumulation of petroleum, in the case of the occurrence of any travelling or flowing of water with oil through the rocks, diminutions in dip might be instrumental in promoting it, the oil tending to become left behind or settle out in the sand or porous rock at such positions of retardation of the current, while the water passed on.

Another hypothesis, termed the "Hydraulic theory," has been advanced in explanation of oil and gas accumulation, such as has been developed by M. J. Munn,‡

* *Trans. A.I.M.E.*, vol. l., pp. 829-842 (1915).
† Ziegler, V., *Econ. Geol.*, vol. xiii., No. 5 (July, 1918).
‡ *Econ. Geol.*, vol. iv., No. 6 (Sept.-Oct. 1909).

and is based on moving water under either hydraulic or capillary pressure as the direct agent in separation and accumulation—instead of gravitational sorting being considered the principal factor, but this theory was formulated chiefly in explanation of the special conditions obtaining in the Appalachian Fields. In this hypothesis, bodies of oil and gas are explained as being "trapped and held between zones of conflicting currents of water," and invading or descending water in unsaturated rocks is postulated. The occurrence, however, of such conflicting currents and descending water in the rocks is questionable.

It has been claimed * that the so-called "hydraulic theory" offers a better explanation than, or several advantages over, that of gravitational sorting, in that :—(1) "It provides an adequate means of forcing the oil and gas from the shales into the pay-streaks of the sandstones or other porous beds. (2) It provides a means of preventing diffusion by sealing up the pore-space surrounding oil and gas-pools by water, under either hydraulic or capillary pressure. (3) It provides an ample source of pressure in both oil- and gas-pools. (4) It furnishes a better explanation of the structural positions of pools of oil and gas, especially in the Appalachian region."

The first-mentioned factor, however, appears to be beside the case in point, since the difference-in-gravity explanation is concerned with the accumulation and separation of the petroleum in the reservoirs, and not with the migration from the shales or clays, when such have provided the source ; this would have been brought about at an early stage by the oil formed in them having been forced out by pressure from the superincumbent deposits, as also by means of selective capillary action, into the rocks where greater porosity favoured accumulation and retention.

* *Ibid.*

As regards the sealing-up of oil- and gas-pools and the source of the pressure therein (2 and 3), hydraulic pressure acting in the manner previously indicated—*i.e.*, forced up the reservoir under a hydrostatic head, and not necessarily of a travelling or descending nature—may also surround, and sufficiently account for, the retention of accumulations, the occurrence of this not being inconsistent with the difference-in-gravity idea of concentration. Likewise the pressure connected with oil- and gas-accumulations may be accounted for in this manner, as well as by the pressure exerted by gas.

While perhaps applicable to the exceptional conditions found in the Appalachian Fields (although in this case the deposits seem largely to conform to certain gentle undulations, and F. G. Clapp * has considered that the evidence there is not altogether inconsistent with gravitational action being the agency in accumulation), the so-called "Hydraulic hypothesis" alone will not explain the structural positions of oil-accumulations in the large majority of cases—as occurring in the elevated part of the reservoir.

Although such influences as moving water and capillarity, etc., as previously noted, have been important and have aided and modified accumulation, it is probable that gravitational sorting must have generally constituted the dominating influence, and in such a manner the situation of the deposits in the majority of cases is best explained.

In short, difference in gravity, or gravitational separation, may be considered to constitute the most important factor in separation and accumulation in the case of structures having defined dips, and of the presence of hydraulic pressures, or of moving waters (or of movement in the liquids); but in other cases of accumulations, as

* *Econ. Geol.* Discussion, vol. iv., No. 6 (Sept.-Oct. 1909).

that of strata having no appreciable inclination, or which are nearly horizontal, capillary segregation would have furnished the principal influence in effecting concentration.

With reference to the pressures existing in oil- and gas-accumulations, such may, of course, be both connected with hydrostatic pressure and that exerted by gas, by either or both of which influences in co-operation the oil in flowing wells may be raised; although in the case of spouters the transmission of occluded gas through the oil would appear to be often the principal means of elevating it—after the manner of air-lifts. Thus, in the oilfields of East Borneo the flowing wells would seem to be dependent on both hydraulic and gas pressures in combination—although very high pressures and prolific wells of gas have been there encountered. In the island of Tcheleken, the cause would appear chiefly to be due to water-pressure, originating from deep-seated springs; while spouters in Trinidad would seem to be frequently due to transmitted gas alone, as also in the case of many Russian examples.

When gas under pressure is present, the water would, of course, tend to assume the same pressure as the gas —although resistance and capillarity in the rocks would tend to reduce it at a sufficient distance from the seat of the gas-pressure. It has sometimes been urged that, if water-pressure were to hold the oil, when under great pressure of gas the latter would tend to force away the oil and water through the rocks, the hydrostatic pressure not being likely to suffice for withstanding it; but, while this idea apparently does not take into account such resistance encountered in the rocks as that due to capillarity and friction, the position of the water would, of course, become adjusted until the pressures were in hydrostatic balance. Should such be the case (*i.e.*, that

the water does not hold in the oil), it would be necessary to offer some other explanation of the manner in which deposits are retained in position, since reservoirs are not always enclosed, as in conditions of lenticular porosity or enclosure by faulting. Thus, except in cases of enclosed reservoirs such as the latter, the pressures in oil- and gas-pools cannot become greater than that exerted by the available hydrostatic head—as modified or adjusted by allowances made for resistance and capillarity in the rocks; although in cases where reservoirs are completely closed to any passage of water, the maximum pressure capable of being exerted by the gas formed may exist, and in such a case this may be greater than that ordinarily assignable to any hydrostatic head.

Furthermore, progress of cementation may be a factor giving rise to increased gas-pressure, by reducing the volume of a reservoir and that of the gas present—or being produced dynamo-chemically from the oil.

Finally, it is worthy of note that the presence of water would thus appear as an indispensable factor in the occurrence of appreciable deposits of petroleum, or of oil-fields, in effecting the accumulation and concentration, as well as the retention of the oil in the reservoirs. In arid regions the work is probably done by deep-seated saline springs, or water from marine sources; and, in this connection, it is noticeable that the few oilfields occurring in desert-regions are situated not far from the sea or inland waters. In the case of the San Juan oil-field in South-Eastern Utah, situated in a semi-arid district, where the strata are supposed not to be water-logged, the conditions might be described as exceptional, although it cannot be said to be established that water does not there exist in the petroliferous formation.

In another way, the presence of water would be needed, so that the argillaceous or cover-rocks may be rendered adequately impervious, there being few sedimentary rocks incapable of a certain amount of saturation.

With reference to the relation of oil-accumulations to large drainage-areas, from which the oil may have been obtained and concentrated, attention has been drawn to the fact that the productive anticlines or domes are frequently situated on the margins of large synclinal basins or geosynclines—which could furnish a wide drainage-area or expanse of strata wherefrom the accumulations could be drawn and concentrated in those folds, while often the further series of folds are less productive or barren—and also, in the case of the productive anticlines, there is sometimes found to be more oil in the flanks belonging to the large synclines or basins than on the other side. Such conditions certainly appear to be strikingly the case in many regions, among others—*e.g.*, in the Rocky Mountain fields, California, Russia, Roumania, and Borneo.

In fact, it may be said that the peripheral regions of large tectonic basins or depressions are in general favourable to the occurrence of, and associated with, deposits of petroleum.

But in considering the relationship to be the effect of the extent of the drainage-area, the supposition of continuous and extensive reservoir-rocks or sand-beds, and an uninterrupted communication and facility for the travel of the oil and water throughout them, has to be made. It should be taken into consideration, however, that the above-mentioned conditions are often explicable by the circumstance (see Fig. 19) that the outer flexures in a folded region are usually of a more favourable type for accumulations and less connected with disturbance

than in the case of those situated nearer the disturbed or mountainous area of the centre of uplift; while at the same time, as the latter is approached, the beds occurring in the successive anticlinal folds become on the whole of lower stratigraphical horizon, and the series concerned may not be so favourable or productive—or may have passed below the petroliferous series.

# CHAPTER VI.

## OIL-RESERVOIR ROCKS, AND THE GENERAL FEATURES OF PETROLIFEROUS STRATA.

CONTENTS—Preliminary Remarks—The Types of Rocks and Deposits acting as Oil-Reservoirs—Relation of the actual Oil-Reservoir to the entire Porous Bed or "Sand-body" and Distribution of the Oil therein—Definitions and the Description of Terms used in connection with the Reservoir, and of the Associated Parts — Arenaceous Rocks or Deposits as Oil-Containers—Porosity—Limestones as Reservoir-rocks and Dolomitization—Other Descriptions of Rocks or Deposits associated with Oil-Accumulations, and the Occurrence of Petroleum or Bitumen in Igneous Rocks—Review of the Descriptions of Reservoir-rocks, as found in the Different Regions or Fields—The actual Oil-containing Capacities of Rocks, and the "Theoretical" and the "Effective" Porosity — Termination and Limits of Reservoirs — General Characteristics of Oil-bearing Series of Strata.

In the foregoing the conditions of accumulations have been reduced from broad generalizations and the extended distribution of petroleum on the large scale, to the structural features associated with the deposits, or limiting the local accumulations.

It now becomes expedient to centralize the enquiry still further, and consider the actual rocks or deposits which afford the reservoirs themselves, wherein the oil and gas are found.

The existence of important deposits of petroleum is just as much dependent on the presence of rocks and strata suitable to retain them as it is on an adequate source and on the structural and other conditions already described, which are necessary to effect concentration; and thus this subject likewise becomes an essential matter of consideration.

Such reservoirs are furnished by strata of various characters, and the following are among the principal types :—

(1) Sands and sandstones.
(2) Argillaceous sandstones and sandy shales.
(3) Fissured, jointed, or cracked rocks.
(4) Porous limestones, including dolomitized, cavernous, fissured, and brecciated limestones.
(5) Occasionally secondary saliferous deposits, such as those of salt and gypsum, with sometimes also associated deposits of sulphur—as, *e.g.*, in some instances in the Gulf Coastal Field, are connected with oil-reservoirs.
(6) Sometimes porous igneous and volcanic rocks (as granites and basalts) are found associated with bitumen, or may contain petroleum, but such cases are seldom of any economic importance.

As uncommon examples of reservoirs or oil-containing rocks, mention may be made of the occurrence of petroleum in detrital beds composed of fragments of coal, as has been noticed in Borneo.

The majority of oil-reservoirs are those composed of sands or sandstones. Arenaceous reservoirs may be consolidated, unconsolidated, or partly consolidated.

In the older formations, as in the case of the Appalachian Fields, they usually consist of consolidated sands, or sandstones.

In the numerous examples of oil-deposits contained in strata of Tertiary age, unconsolidated sands are usual, while sometimes coarser materials or gravels, as, for example, in some instances in California, afford reservoirs.

Seldom is it found that the entire porous bed, or

"sand-body," is coincident with the actual oil-reservoir, which may only partly occupy a portion thereof, or may vary in the degree of oil-saturation, while the oil may occur in lenses of coarser grade materials and of greater porosity, such as are found in the Appalachian Fields, and known as "pay-streaks." Such distribution of the oil in the porous beds is usually in accordance with the varying grade and porosity of the materials, the oil—as previously shown—occurring in those parts of the sand-body that have the greater porosity or coarser grades of materials.

Thus, the use of the following terms has been distinguished or defined. A "sand-body" is any stratum or bed of sands or sandstone. The "reservoir" is that portion of the sand-body, or other suitable porous rock, which is sufficiently porous to be capable of containing or yielding oil or gas. It may be used to include the whole of the suitable porous mass—whether in respect of the portions containing water, oil, or gas. A "pay" is the portion of such a reservoir from which commercial oil or gas can be obtained, and may be called "oil-pay" or "gas-pay," as the case may be, but the term is generally used to denote an "oil-pay." It is sometimes used to denote any petroliferous horizon or bed, or oil-sands; but, in order to accord with the derivation of the word, it would seem that the term should properly be applied to payable deposits; while "oil-sands," "oil-horizon," or "petroliferous beds or seams" are terms or phrases that may be utilized for wider descriptions. The term "oil-pool" is properly applied to the whole of a continuous oil-reservoir, or that portion containing oil.

The "roof" or "cover" of a reservoir usually denotes the impervious—or rather, "less porous"—bed covering the sand-body or porous rock; but the term may also denote the upper bounding surface of a reservoir or oil-

deposit, when such may not be located at the lithological dividing-line. A passage in the lithological character of the constituents is, of course, more usual than an abrupt division, so that the actual limiting surface of the oil-reservoir is not often marked by any hard and fast lithological break, or abruptly terminated by the base of an impervious covering rock. Neither can the covering or subjacent beds of an oil-reservoir be generally or strictly described as "impervious," the oil being usually situated in the latter on account of greater porosity and selective segregation, while the surrounding shales are generally more or less water-wet.

In like manner, the features just described would apply to the lower limiting surface, or base, of the reservoir.

Sandstones are, of course, variable in the proportion of argillaceous material which they contain, merging into sandy shales, although the amount of contained argillaceous matter would tend to reduce the porosity accordingly. Sometimes, however, rocks which are virtually sandy shales are found to be oil-bearing or to hold a considerable amount of oil.

Likewise, the degree and quality of the cementation will tend to influence the porosity of a sand-rock, and thus the porosity and the amount of oil contained may vary according to the amount of such cementing material, in the same stratum. Consequently, oil-bearing sand-beds are often found to vary considerably in their porosity and oil-bearing quality—often in the same area, or within comparatively short distances, on account of this condition of cementation, and a good oil-bearing sandstone may locally become so strongly cemented as to become in this manner almost or entirely barren.

To such a condition may often be ascribed the irregular and capricious results experienced in some fields, not

infrequently from borings in proximity, where other conditions are equal.

**Porosity.**—The greatest porosity in sandstones is, of course, related to the presence of a spheroidal nature of the grains, as also to comparative uniformity in size, while the relative absence, or paucity, of cementing material, or of argillaceous matter—clogging the pores, will also tend to higher porosity.

Grains of many sizes and irregular in shape tend to form a more compact rock, the smaller grains filling the interstices between the larger.

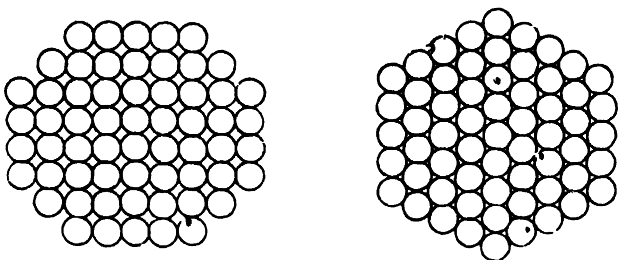


Fig. 22. Fig. 23.

Diagrammatic Arrangements of Spheroidal Grains and Maximum and Minimum Porosities.

Furthermore, the arrangement of the grains, when of a spheroidal structure, will affect the amount of porosity. Thus, the arrangements of the spheres as in Figs. 22 and 23 will give maximum and minimum porosities, in the case of spherical grains, with which void-capacities of from about 45 to 25 per cent. are respectively obtainable—according to their groupings.

It is not likely, however, that the grains will ever become naturally arranged, or remain, as in Fig. 22, nor are they generally to be found so closely packed as in Fig. 23—unless subjected to very great pressure. A somewhat more open packing than in the latter arrange-

ment is usually the case. Thus, under the most favourable conditions, a sand or sandstone may furnish a void-capacity of from 20 to 30 per cent., although porosities of as much as 30 to 35 per cent. have been reported to have been found—as in the case of some water-sands.

In some of the richest oilfields, and reservoirs, in the world, as, *e.g.*, in Russia and the Baku region, a saturation of about 25 per cent. in the oil-sands probably occurs.

It has been declared that the porosity of sands is liable to become increased where they are submitted to pressure, on account of disturbance of the original natural packing—although the opposite would seem more generally to be the case.

Sands—generally, of course, deposited from water—cannot be said to have been originally and naturally deposited or packed with the minimum amount of interstitial volume of the voids.

Taking, for example, the instance of spherical grains—which afford maximum porosity, such may be arranged as in Fig. 22, giving maximum porosity, or as in Fig. 23, giving minimum interstitial space. While it is unlikely that the grains should ever become naturally arranged as in Fig. 22, it is likewise improbable that they would fall into place with the closest possible degree of packing, as in Fig. 23, especially when the grains are of various sizes, and irregular in shape, and an intermediate, or somewhat open, arrangement in packing would be most generally the case. But the introduction of greater pressure would tend to force the grains into a position such as that shown in Fig. 23. Such a condition is often noticeable in instances where locally greater pressure has been exerted—as in the vicinity of faults.

Another kind of porosity, however, may come into play by means of pressure or folding—that which has been

named "induced porosity,"* to which allusion has already been made in a previous section, on account of the formation of joints, fissures, cracks, cavities, etc., as before described.

Such induced porosity may, of course, be expected to be associated principally with consolidated rocks; although cavities, cracks, etc., may also occur in unconsolidated sands, while, when under the great pressure due to the weight of the superincumbent masses, or that connected with tectonic movements and folding, the unconsolidated deposits may behave almost in the manner of consolidated rocks.

Such fissures and cracks or jointing sometimes also give rise to the provision of reservoirs in impervious or insufficiently porous rocks; thus, fissured or fractured and jointed shales are in some localities found to contain and yield oil, as in the well-known instance of the Florence Field in Colorado, as also in Alaska and Mexico, while some cases of this description of reservoirs are found in the Appalachian Fields. Similarly limestones may in this manner become fractured or jointed, and thus become capable of holding petroleum and furnishing reservoirs, as has occurred in some parts of Mexico, where sedimentary rocks have often become shattered by the igneous intrusions, which sometimes themselves have become so shattered and cracked as to constitute a porous rock, and have the capacity of containing petroleum.

**Limestones as Reservoir-Rocks.**—Except when arenaceous to any considerable extent, or partaking of the nature of marls—into which limestones may, of course, merge, limestone proper has usually too low an average porosity to be suitable to act as a reservoir or to allow of yielding oil, although limestones are sometimes more or less impregnated with petroleum. When, however,

* Lauer, A. W., *Econ. Geol.*, vol. xii., No 5, p. 486 (Aug. 1917).

there is an acquired porosity, by means of fissuring, jointing, water-channelling, or that brought about by the process of dolomitization, limestones may furnish important, and sometimes prolific, reservoirs. Dolomitized limestone, as affording suitable conditions for containing oil, has already been mentioned, the rock on dolomitization contracting in volume, thus occupying less space and in this manner becoming porous or vesicular.

In this process of dolomitization—which seems to occur principally in the limestones of the purer variety—the calcium carbonate of the limestone becomes altered to a double carbonate of calcium and magnesium, the accompanying contraction of the rock resulting in the formation of interstices and cavities and numerous interspaces between the crystals of dolomite, whereby exceedingly great porosities are sometimes created. In the United States the dolomitized Trenton Limestone affords notable examples of this kind of oil-bearing reservoir-rock, while in Southern Texas dolomitized limestone-reservoirs, of extraordinary capacity and pore-space, are found in some of the oil-pools and saline domes, as, for instance, in the noted pool of Spindle Top, where cavities as large as an inch in diameter, and probably sometimes larger, are contained in a dolomitic reservoir-rock, which has been estimated to be capable of holding as much as a third of its volume in oil. Furthermore, reservoirs of very great capacity are also found in fractured and water-channelled limestones, as, for example, in Mexico—the Tamasopa and San Felipe Limestones, etc. In some cases fragmental or detrital limestones serve as oil-bearing rocks—as, for instance, in Western Persia, etc.

Finally, among typical examples of limestones comprising the reservoir-rock, may be noted those in North

America—viz., in the Appalachian and Lima-Indiana fields, as also the dolomitic occurrences in the Gulf Coast fields; and, further, those in Canada—*e.g.*, the cases of the Corniferous and Niagara Limestones, etc., while other such instances are found in Mexico, Persia, Egypt, Alsace, etc.

In regard to other kinds of rocks, of a different character, found in connection with oil-accumulations, reference may be made to the occurrences in association with secondary water-deposited saliferous beds of salt, gypsum, and also of sulphur, in the saline-dome pools of the Gulf Coast fields.

With reference to igneous rocks and the occurrence of petroleum, their porosity is generally so very low, as to be insufficient to hold any appreciable quantities of oil, or furnish any reservoirs—except when such rocks have been shattered, in which condition, as above mentioned, petroleum is sometimes found in them, while in the case of vesicular volcanic rocks which might be capable of containing some oil in the interspaces, the vesicles are not usually in communication. It will thus be seen that the likelihood of finding conditions suitable for oil-accumulation, or of the occurrence of any appreciable deposits of petroleum, in igneous rocks, is very slight, even when conditions may be favourable.

Small amounts of petroleum, however, are sometimes found in granites and basalts, etc., as in Quebec, Oregon, and Mexico, etc., as also in the Tertiary eruptive rocks of the Queen Charlotte Islands, B.C. In the last-mentioned locality bitumen is found in vesicles and in the interior of amygdales in the Tertiary basalts at several places, among others at Lawn Hill on the eastern coast of Graham Island, and on the eastern coast of Moresby Island; also on the western coast of Graham Island in the neighbourhood of Tian Point. In this case the

are sometimes found in Trinidad—in the earlier petroliferous strata. Limestones and dolomites as the oil-containing rocks more usually occur in the older formations, as in the Palæozoic of North America, though such are also found in Secondary and Tertiary formations in Mexico, Alsace, the Gulf Coast Field, Persia, Egypt, etc. While in some cases, hitherto described—*e.g.*, in Colorado and Alaska—fissured, jointed, or cracked shales act as oil-reservoirs.

In respect of the oil-containing capacities of rocks, the difference between the actual or theoretical porosity and the effective porosity should be distinguished. As all the pores in a rock may not communicate, and in some rocks such a condition may occur in a greater degree than in others, some rocks may afford only a relatively low yielding capacity when the actual porosity may be high. Thus, in the case of rocks having large vesicles not in communication with one another—as in some types of volcanic rocks—such may contain a very high theoretical porosity, while the yielding capacity may not be of any account.

Moreover, consideration must also be taken of the amount of oil recoverable from an oil-bearing rock, for, except in the case of almost complete displacement by water, any approximation to complete extraction of the oil cannot be realized, a considerable amount of petroleum remaining in, or adhering to, the rock. Furthermore, in cases where the pores in a rock are very small, the oil which may be retained in such is not readily withdrawn —on account of frictional resistance, adhesion, and capillarity.

Hence, on account of these circumstances, tests for the determination of porosities made on rock-samples may give somewhat excessive results, or an incorrect idea as to the effective porosity and yielding capacity

of the rock, since a number of non-communicating pores would become opened on the surface of the rock-sample, while also the presence of pores which might be too small for the withdrawal or recovery of the liquid would add to the amount absorbed and contribute to the theoretical porosity.

**The Termination and Limits of Reservoirs.**—The vertical limits of an oil-reservoir have already been described, the porous reservoir-stratum being usually surmounted and underlain by an impervious or, more correctly speaking, less porous rock or deposit, between which there may not be any hard- and fast-line or definite division, but sometimes a gradual transition may occur, the one grading into the other. While, in the case of varying porosity in a reservoir-rock—arenaceous or of limestone, the limits of the oil-pool may lie within the body of the rock or bed—and not be bounded by its limits. In like manner, differential cementation may limit a reservoir, or divide it into separate "pays." Moreover, the presence of water may, of course, terminate the actual oil-containing portion of the reservoir.

As regards the lateral termination of an oil-reservoir, this may take place in several ways, and may occur by (1) thinning-out or lenticularity of the bed, (2) variation or decrease in the porosity of a rock, (3) faults, (4) differential cementation, (5) asphaltic or paraffinaceous inspissation and sealing, or (6) the intervention of an igneous intrusion; as also, of course, by the position of the water in the reservoir.

The first two of the above-mentioned conditions appertain, of course, to lateral variation. An arenaceous stratum may merge into argillaceous, or less porous, material, gradually thin out, or the sand-beds may be lenticular; while, in some instances, as sometimes found

among the petroliferous strata in the Zechstein (Permian) Series of Central Russia, a very abrupt change from an arenaceous bed to an impervious marl or other rock may occur. An oil-reservoir, moreover, may also be bounded by variations in texture and porosity within

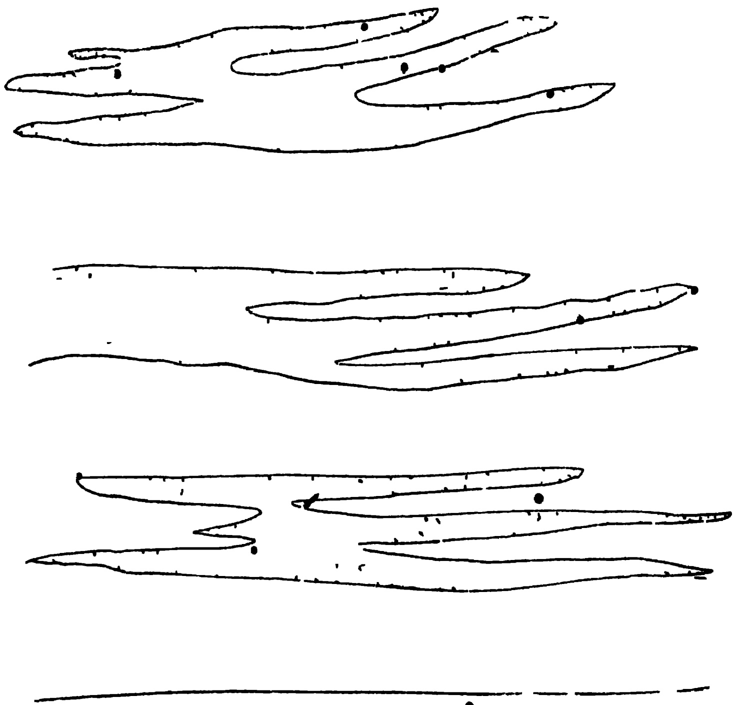


Fig 24 —Irregular Shapes in Sand bodies and Reservoirs

the sand-body, as in the case of lenses of greater porosity, which have already been described elsewhere.

In the case of lenticular structure in sand-beds, the latter are more frequently not of a well-defined approximately lenticular form, or in regular lens-shapes

(as in text-book diagrams), and sometimes the sand-bodies may not taper off regularly at each end, but even assume fantastic shapes, bifurcate, or split up into several arms (see Fig. 24).

As regards the termination of a reservoir by a fault (3), the effect of faults in bringing into juxtaposition porous petroliferous beds and impervious or less pervious rocks, and the consequent formation of accumulations on the down-dip side, has already been noticed in a previous chapter; in this manner faults form the termination of the reservoir on one side, which is the up-dip side of it. Although it is usually on the up-dip side of a reservoir that faults afford the termination, it can also become terminated by a dislocation on the down-dip side—in cases where a bed which already contained oil may have become interrupted by a subsequent fault. In this way, sometimes, each side of a reservoir may be terminated by faults, as also in the case of horizontal, or nearly horizontal, oil-bearing strata intersected by faults. This condition, of faulting terminating a reservoir on both sides, not infrequently occurs in cases where the oil-bearing formation has been much faulted—as, *e.g.*, in the island of Tcheleken, where the petroliferous beds are frequently thereby interrupted and displaced.

Variations in the degree of cementation, and consequently in the porosity and petroliferous condition of arenaceous deposits have been above described. In this manner a reservoir may be terminated by portions of the sand-body becoming cemented to such a degree that there is insufficient void-capacity, or the interstices of the rock may be completely filled. Such is more usually caused by calcareous cement, but may also be brought about by siliceous cementing, or by the sand or sandstone passing into a very ferruginous rock.

As previously described, in connection with the origin

of accumulations, in the case of outcropping and denuded petroliferous strata, accumulations or oil-reservoirs may become sealed up by the inspissation of the oil and the deposition of residues. Oil-reservoirs may in this manner be retained by the inspissation of either asphaltic or paraffinaceous oils, and respectively accompanied by the deposition of either asphalt or ozokerite, as also the waxy residual material which is the remaining product of some oils of a paraffin base, and may clog the pores—as is found in some cases in the Appalachian Fields, *e.g.*, in Pennsylvania, also in the San Juan Field (Utah), and elsewhere. Such paraffinaceous deposits or sealed outcrops in connection with paraffinaceous oils are not so noticeable or conspicuous as those produced by asphaltic oils, or asphalt-sealed outcrops (in which case the deposits of asphalt may be large and conspicuous, such as often mark outcropping petroliferous beds, and are sometimes of very great size, as in the instances of the "pitch-lakes" in Venezuela and Trinidad). Deposits of ozokerite, moreover, which are in a similar manner due to inspissation, indicating a residual product of petroleum of a paraffin base, occur in many regions where such oils are found—notably in the Carpathians, Tcheleken, etc.

Intrusives may intercept and thus bound oil-bearing beds, acting in a similar manner to faults; although sometimes the rock may have become shattered, cracked, or jointed, and consequently allow the egress of the petroleum through the igneous rock itself to the surface, while such may also sometimes take place at their junction with the sedimentary rocks when there is any opening to the surface between the dyke and the penetrated strata. Thus, the outcrops of intrusives and dykes, passing through petroliferous strata, are often marked by lines of seepages along their course.

**The General Characteristics of Oil-bearing Strata.**—Oil-bearing series of strata most commonly (especially in the Tertiaries) consist of series of shales or clays with intercalated beds of sands or sandstones, the former or more impervious rocks predominating. For, as previously observed, such comparatively thin porous beds amongst a predominance of impervious beds would be more likely to have a strong saturation than in the case of thick or massive sands, sandstones, or other porous beds, wherein the oil would be liable to dissipation—although in some exceptional cases comparatively thick beds are found to be highly saturated throughout. In some cases, however, where accumulations occur at places of variation in the texture of rocks, as by selective segregation and capillarity, thick or more massive and persistent strata may contain the deposits, the reservoirs being confined to certain portions, which have the requisite porosity, as in the case of lenticles of greater porosity, or "pay streaks," contained in massive arenaceous strata; as also in the case of accumulations in limestones, where the reservoirs occur in the more porous parts—resulting from dolomitization or otherwise.

The alternating series of argillaceous and arenaceous strata are, however, the more commonly associated with oil-deposits, while particularly typical of the Tertiary deposits. Such series of deposits might not inaptly be termed "oil measures."

Not infrequently such series may be also coal-bearing, and seams of coal or lignite are interstratified with the petroliferous beds, as in several Tertiary examples—a noteworthy and perhaps the most pronounced instance of which is found in Eastern Borneo.

Such petroliferous series may extend over a great vertical range, which may sometimes amount to 3,000 feet, or even more, in actual thickness. Sometimes all the beds

Appalachian Fields, as also in those of the Mid-Continent, etc., the strata associated with oil-deposits are extensive and persistent.

The vertical range of a productive series may be terminated by the strata containing water, or gradually by the increase in the amount of water present in the petroliferous beds; or the oil-bearing series of beds may come to an end by a change in the lithological character of the strata, or to another formation. An unconformability, moreover, may abruptly terminate the vertical series by bringing in another and non-petroliferous formation.

# CHAPTER VII.

## DIRECT INDICATIONS OF PETROLEUM.

CONTENTS—(1) General Observations—General Description of Indications—Oil-Exudations or Seepages — Emanations of Gas—Mud-Volcanoes, and New Upheavals and Islands — (2) Solid Hydrocarbons and Bitumens—General Description—Primary Grouping and Broad Classification — Impregnations and the Purer Forms — Occurrences of Superficial and of Subterranean Origin—Ambiguity and Confusion in the Use of the Terms "Bitumen," "Asphalt," and others, and the General Nomenclature — Differentiation between the Bitumens and Coals, and the Graduation to the Pyrobitumens—Various Definitions of the Term "Bitumen," etc., and the General Classification of the Series—Description of the Native Types of Solid Bitumens—General Properties and Mode of Occurrence—The Names that have been given to the several Varieties and their Classification—"Asphaltites," "Asphaltic Pyrobitumens" and "Kerites" — "Manjak"—"Uintaite" or "Gilsonite" — "Tabbyite" — "Piauzite" — "Grahamite"—"Elaterite" "Coörongite"—"Wurtzilite"—"Albertite" — "Nigrite" — "Impsonite" — "Ozokerite," and the Native Paraffinaceous or Wax-like Hydrocarbons—"Positive" and "Impositive," "Direct" and "Indirect" Indications.

(1) ATTENTION is, in most cases, first attracted to a petroliferous region or prospective oilfield by the existence and discovery of some sort of direct surface-indications of petroleum. These may be exudations or seepages of oil, outcrops of petroliferous strata, deposits of the more solidified products or solid residues, such as asphalt, ozokerite, or other solid bitumens, emanations of gas, and also mud-volcanoes. Although in some cases the discovery of oilfields has resulted from "wild-cat" drilling, or sometimes accidentally when boring was being carried out for another purpose—as in the instance of the original discovery of oil in America, when salt was being sought in Pennsylvania. While in other

cases geological investigation has first indicated the existence of petroliferous conditions in areas where direct surface-indications are not evident, either by means of continuation from, or analogy with, regions which are known to be petroliferous or wherein oil has already been obtained. In most great fields, however, the discovery-wells were sunk amidst surface shows, which gave rise to their location, and in many cases such areas, where the seepages are well marked and the original wells sunk, have later proved to be the most prolific.

In the older formations containing petroleum such direct surface-indications are not generally so marked or so abundant as in the case of those which are of later age, and they are often particularly apparent and abundant in petroliferous areas of Tertiary age. As has been seen, large or important deposits of petroleum are seldom found in the older formations, unless these be comparatively little disturbed. Such superficial indications as seepages, exudations, emanations, etc., are, of course, the expression of the dissipation and the gradual waste of the oil and gas, and the older the formation is, the longer has been the time during which such a process of gradual leakage has continued, tending to result in the exhaustion of the reservoirs and the dissipation of their contents. Thus, where oil-accumulations are found in strata of earlier age, or under conditions of little disturbance, as in the case of the Appalachian Fields, a comparative paucity of surface-indications is often characteristic, or they are not usually very pronounced. Moreover, petroliferous areas where abundant and copious exudations and "surface-shows" occur are more frequently unfavourable for commercial results, and such is often the case even where the geological formation is comparatively young.

It is, however, by the presence and discovery of direct indications that attention is usually first attracted to petroliferous areas or formations, and that, in conjunction with the geological conditions, accumulations of oil or gas are revealed. Thus, the detection, recognition, and significance of indications of petroleum are of importance, as also their distinction from pseudo-indications.

Direct indications of petroleum—which may be solid, semi-solid or viscous, liquid or gaseous—may in short be grouped as follows:—Exudations, or seepages, of liquid petroleum, including those due to the outcropping of a petroliferous bed, and seepages from below—as through joints, cracks, fissures, or fault-planes; exudations of viscous inspissated petroleum, as "mineral-tar," "piss-asphalt," etc.; deposits of solid residues, such as asphalt, ozokerite, etc., which may occur either at the outcrop of a petroliferous bed, or infilling fissures, fault-planes, etc. While there are also the various types of solid hydrocarbons, or high-grade native bitumens, which are found (*e.g.*, those known as manjak, uintaite, grahamite, wurtzilite, albertite, etc.), and usually occur in veins and as the infillings of fissures, cracks, or fault-planes. Lastly, emanations of inflammable gas (composed of hydrocarbons) and mud-volcanoes, which may also be accompanied by exudations of oil.

In addition, substances other than petroleum or those containing hydrocarbons may often be regarded as possible or probable indicators—in virtue of their frequent association with petroleum (as described in Chapter II.); among these are gypsum or selenite, and common salt and saline water or brine, as also other associated salts. Sometimes, under certain conditions, the presence of sulphur and sulphurous gases or waters may be regarded as an indication of the probable occurrence of petroleum.

**Oil-Exudations or Seepages.**—Exudations, seepages, or oil-springs may, of course, be due either to the actual outcropping of an oil-bearing bed or to the seeping-up of the oil (through fissures, cracks, fault-planes, or other channels) from below; in the latter case, they are more often accompanied by some gas, while in the fissures sometimes the solidified, or more nearly solid, residues resulting from inspissation may be found.

They perhaps more frequently belong to the latter type—especially in the case of occurrences along or near the axial region of the anticlinal folds. It has been suggested, by Dr. G. Bonarelli, to classify seepages as "normal," "longitudinal," and "lateral," according as to whether they are respectively seeps from below (or what might be called migratory exudations), petroliferous outcrops (exposed by the erosion of the beds) with incidence in the axial region, or petroliferous outcrops with incidence on the flanks of the anticlines.

The oil generally found in surface-exudations is naturally of an inspissated character, and devoid of the lighter portions. In some instances, however, occurrences of remarkably light oil are found at the surface, and the character of the oil in exudations varies from thick tarry or pitchy inspissated material to these light oils. Among examples of the latter may be mentioned those found at Lizard Springs in the south-east of Trinidad, as also that at Kala Deribid in Persia In the former instance a copious seepage of a remarkably light crude oil, of a pale brown-green colour, yielding about 50 per cent. of kerosene, together with some more highly volatile constituents, is found, and the crude oil can be burnt in a lamp without treatment. Somewhat similar oil, occurring as a seepage in a test-pit, which could be used in the crude state in a lamp, was found by the writer in North-Western Borneo (as mentioned

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*Photo by T. Sutton-Bowman.*

**Fig. 25.—Impregnated Eocene Beds (marls and sandstones), near Gebel Tanka, W. Sinai.**

in Chapter II.). More frequently seepages are of thick and viscous oil, which is often black and tar-like.

In some cases, where the outcrop is covered with soil, a petroliferous or asphaltic condition, or odour, of the soil is all that is discernible; but sometimes, where there is much vegetation, the leaves lying on the ground, or some of the roots and branches, may have become blackened, so that the occurrence is readily noticeable—such as are sometimes known as "black spots," to the appearance of which the presence of black pitch or tarry residual matter in the soil also contributes. Sometimes the occurrence of slightly petroliferous or asphaltic sandstones is all that indicates the presence of oil-bearing strata, although when such an outcrop of petroliferous sandstone or sandy shale occurs in streams, or is covered with water, a streak of oil is generally to be seen issuing from it. In some localities patches or deposits of asphalt, or pitch, constitute the only indication to be found of the existence of subterranean sources of petroleum, although usually in such cases some exudations of more liquid petroleum are revealed in excavations.

Seepages or petroliferous outcrops can often be discovered and traced in streams by observing and following up the occurrence of a film of oil on the water. Sometimes the smell of the oil from a seepage is sufficiently strong or noticeable to attract the prospector from a distance.

In prospecting and the search for oil along streams or on pools, it is, of course, desirable not to be misled by the occurrence of the iridescent films due to iron oxide, as also by the presence of vegetable oils or oleaginous matter of vegetable origin—such as saps, resins, etc. But iridescent and non-petroliferous scums, such as are commonly found on the surface of pools, etc., usually break up into fragments on being stirred—behaving

unlike the films composed of liquid petroleum. Exudations or streaks of ferruginous material and water are very common along the banks of rivers at low water, and such occurrences have often been mistaken for indications of oil, and have led to long, difficult, or costly journeys —in order to investigate the reported occurrences of petroleum.

Sometimes large and extensive asphaltic deposits, or "pitch-lakes," are found, these having generally resulted from the inspissation and residuum of petroleum—although accumulations of this nature are not invariably connected with liquid petroleum. Among such occurrences, a notable instance is that of the well-known "pitch-lake" at La Brea in Trinidad, which attained notoriety and commercial importance before it was recognized as an indication of petroleum, or before the oil was commercially produced or exploited, and it was by drilling in the vicinity that the oil was discovered. Other smaller but considerable deposits occur in the island, while pitch-lakes of greater size are found on the mainland in Venezuela—*e.g.*, that of Bermudez. That of La Brea, Trinidad, has been estimated to contain as much as 10 million tons of the asphaltic emulsified material.*

Deposits of asphaltic or bituminous material, however, cannot be considered as invariably an indication of petroleum or of the presence of liquid oil.

An instance of enormous and widespread interstratified deposits of asphaltic or bituminous material is afforded by the famous MacMurray bituminous, or so-called "Tar" sands, which extend for over one thousand square miles in North-Western Canada. But, although perhaps the greatest indication of petroleum in the world, it does not seem to constitute an indication of the existence

* Beeby Thompson, A., *Trans. Inst. M. and M.*, vol. xx., p. 247, 1911.

of commercially valuable or liquid oil; at least, so far, such would not seem to be obtainable—either in commercial quality or quantity—in that formation, although a viscous tarry material is found in these beds at depth, while from a well in the district of Fort Mackay, a somewhat more liquid petroleum was obtained—although also in a condition unsuitable for ready extraction or production. The bituminous deposits of the "Tar Sands" are, however, exploitable and yield oils of commercial value, by means of the distillation of the solid material.

**Emanations of Gas and Mud-Volcanoes.**—Generally a manifestation of the presence of oil-deposits or petroliferous strata is shown in the occurrence of some evolution or shows of inflammable gas—either accompanied or unaccompanied by any traces of oil.

Such escapes of gas are, of course, only conspicuous or readily noticeable—unless very strong, when passing through any water, or oil, on the surface of the ground, or when they occur in rivers, streams or pools of water, or, as not infrequently happens, beneath the sea. Such emanations from dry ground can sometimes, however, be detected by igniting the gas; thus, in Barbados, such inconspicuous emanations in the petroliferous formation are frequent, the presence of which ignition only may bring to notice. In the case, however, of the so-called "bubbling spring," near Turner's Hall, in the same island, there is an ebullition of water due to the evolved gas, unless the spring is dry (although in this instance the evolution of gas appears to have subsided since some borings were sunk in the vicinity).

Reservoirs or accumulations of natural gas alone, without or independent of any oil, do, of course, occur, and may be attended with some escapes, or give rise to gas-shows—as also in the case of gas connected with

the presence of coal, although the structural conditions favourable for much accumulation of natural gas, or the occurrence of gas-fields, are generally those of little disturbance, so that such natural escapes are not so very common. Otherwise, the stores of natural gas might have long since become depleted.

Natural gas principally consists of methane—as also coal-gas; although the gases connected with petroleum are generally largely composed of this hydrocarbon.

Moreover, the evolution of inflammable gas—which is also methane—resulting from the decay of superficial or recent organic matter, *i.e.*, "marsh gas," is, of course, a common occurrence, especially in regions of much vegetation and tropical countries, and is not infrequently confounded with the gaseous indication of petroleum. But usually the environment, and the presence of the rotten material, the fermentation of which produces the gas, as also the superficial origin, afford sufficient clue for the identification of marsh gas. Thus, in the case of marsh gas, when the ground is subjected to pressure or trodden on, or the bottom of the water, pool, or mire is stirred with a stick, an increase in the evolution of the gas generally takes place.

Marsh gas, or methane, burns with a very faintly luminous and blue flame, as also natural gas, when this is for the most part composed of methane; but the flames of the gases connected with oil-deposits generally have a more yellow colour, while natural gases alone sometimes burn with a distinct yellow colour—as in the case of the gas found at Heathfield (Sussex).

Samples of gas, when evolving through water, may be easily collected by means of water-displacement in a bottle, and a chemical and physical examination of the gas may disclose the nature of it, or the likelihood of it

being that connected with petroleum. The nature of gas from a "show" may sometimes be recognized by its odour, which may be sufficiently characteristic of the gas pertaining to petroleum, although this is sometimes masked by the intermixture of sulphuretted gases; but the latter are not infrequently present in connection with petroleum, especially when the oil contains sulphur compounds. The gas of petroliferous origin is generally of a heavier type, or more or less of the nature of "wet gas," or it may contain minute liquid particles of oil, and if any condensation is observed to take place, or globules of oil are found in association with the gas, this would be indicative of a connection with petroleum.

The submission of the gas to pressure may show some result, or, as suggested by Messrs. Johnson & Huntley,* in the case of well-head gas, a rough test might be made by passing the gas through iced water, so as to note whether any condensation takes place or film of oil appears.

Other gases that may be observed as emanations from the ground are sulphuretted hydrogen, sulphur dioxide, carbon dioxide, and sometimes hydrochloric acid, as also ordinary air. Such emanations can, of course, be distinguished from those of petroleum gases and natural or marsh gases by their non-inflammability. The occurrence of the first-named gases can most frequently be assigned to volcanic action—when the presence of such is to be suspected.

The sulphuretted gases are not infrequently found with petroleum-deposits, and they may result from the decomposition of sulphur compounds in the oil, or of gypsum and other sulphur compounds which are often associated with petroleum. Indeed, the presence of

* "Principles of Oil and Gas Production," p. 85. 1916.

these gases has sometimes even been regarded or included as an indication of petroleum, although they are of wide and general occurrence, resulting from the decomposition of sulphur compounds—both organic and inorganic; while the evolution of such gases on the grand scale constitutes, of course, a common and usual phenomenon in connection with volcanic or solfataric conditions.

**Mud-Volcanoes.**—In many petroliferous regions, especially where conditions of steep folding and disturbance prevail, mud-volcanoes are found, and afford one of the indications of petroleum.

These are eruptions of gas, fine argillaceous material or mud, with water, often attended with solid ejectamenta from the subjacent strata, sometimes accompanied by some petroleum, but occasionally without any appearance of the latter, while in some cases asphalt may be present in connection with them; gaseous hydrocarbons, with water, affording the active agent. In some occurrences, however, gas is not noticeably present—so that they are in fact just "mud-springs." The erupted matter or mud very commonly consists of a very fine, pale-grey, argillaceous material, with water—often a fine emulsion of oil, water, and this material.

They often simulate remarkably, on a miniature scale, real volcanic phenomena, both in the type and form of the cones which are built up, and in the manner of their eruptivity; and like the elevations arising from true volcanic action—which differ in form and contour according to the character and viscosity or fluidity of the lavas composing them, as also when built of solid ejectamenta, the shape of the cone in mud-volcanoes will vary according to the consistency of the ejected material. When the material is stiff, or viscous, or much solid material (such as ejectamenta of rock-

[To face p. 162.

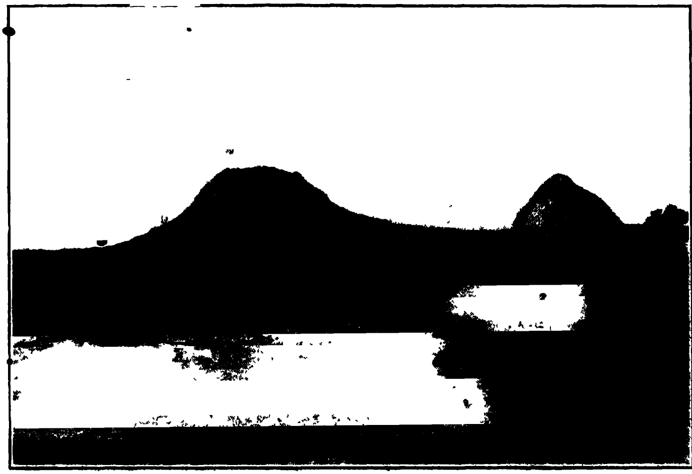
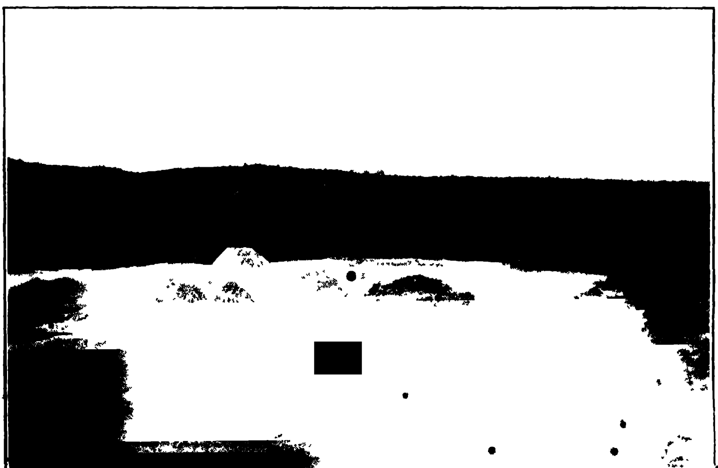


Fig. 26.—" Mud Volcanoes," Minbu, Burma.



*Photos by Major T. R. H. Garrett.*

Fig. 27.—" Mud Volcanoes," Minbu, Burma.

fragments) is present, the resulting elevation will be steep and conical; but, when the mud is in a more liquid condition, or accompanied by much water, the accumulation formed will be depressed, flat, or widespread; or there may be just a stream of mud issuing from the vent, or a pool of muddy water with discharges of gas. In some cases, there is merely a patch of dried mud, sometimes of large extent, which may be strewn with ejectamenta, often accompanied with small cones in occasional activity. Being composed of soft and readily denudable materials, the accumulations are usually washed away with comparative rapidity, when they are inactive.

In like manner, mud-volcanoes have their periods of repose and their epochs of activity, with bursts of eruptivity which are sometimes of considerable violence.

Occurrences of the nature of mud-volcanoes are not, of course, limited to petroliferous conditions, and similar phenomena are found unassociated with petroleum, as, *e.g.*, the "salses" and "salinellen," occurring in Sicily, Italy, etc., and the mud-cones and eruptions, in which steam affords the active agent, occurring in connection with true volcanic action or solfataric conditions. There are, moreover, the gaseous emanations which denote a phase of vulcanism still further advanced, or approaching that of final extinction, with evolution of the sulphuretted gases, with sometimes nitrogen, or carbon dioxide (as in the case of the "moffettes" of the Eifel).

Mud-volcanoes, of the petroliferous type, being generally associated with conditions of sharp folding and disturbance, thus do not, as a rule, afford a favourable sign. Although some regions where they are conspicuous or their development is pronounced—as, *e.g.*, in Burma and Trinidad, as also in some parts of the region of Baku—are not unfavourable or unproductive, their

presence more often, especially when remarkably developed, denotes conditions of too acute folding and too great disturbance in order to favour good results, or they betoken a production but ephemeral in character —as, *e.g.*, in Kertch, Taman, North-Western Borneo, etc. In Trinidad, moreover, where a considerable number of mud-volcanoes are found, the folding is generally sharp and the strata more or less disturbed. In Tcheleken, on the other hand, where the strata are greatly disturbed by faulting, but not by folding, ordinary mud-volcanoes do not occur.

Mud-volcanoes are sometimes held to be of a more or less superficial character and origin, as when petroliferous beds covered with argillaceous strata or material come near the surface, the occurrence of gas beneath the covering of shale or clay, or other impervious material, forcing up the latter. Although some phenomena of this description may be of such a nature, and minor occurrences of such shallow origin take place, the fact that mud-volcanoes are of more or less deep-seated origin is often evinced by the presence of fragments from lower formations amongst the ejectamenta—as exemplified in Taman, Russia, Trinidad, and elsewhere. Moreover, in many petroliferous areas, where such conditions suggested as accounting for the phenomena and as suitable for the shallow mode of origin do exist, mud-volcanoes are not found.

Frequently they are disposed, although often in groups, in a linear arrangement, and, as might be expected, more or less follow, and are usually situated on, the anticlinal folds; they appear, however, to be most often formed along lines of dislocation or fracture, to which circumstance the occurrences, especially in the case of the deeper-seated and more important types, are doubtless generally due, such faults being sometimes

longitudinal—along the flexure, while transverse dislocations may also give rise to the required conditions on the crest of the anticlinal fold. And it is the ground and pulverized argillaceous material or "fault-rock," arising from the dislocation, and discharged by the gas and water, that produces the grey mud composing the principal and characteristic emission from the vents. The practice, however, of linking up and connecting the positions of mud-volcanoes with lines of anticlinal folds —as has sometimes been done, is, especially in little-known country, much to be deprecated, and has not infrequently led to disastrous results.

In many petroliferous regions mud-volcanoes are entirely absent. As might be expected, mud-volcanoes are not usually found in regions where the strata are not much folded, disturbed, or fractured, and would not be likely to occur under conditions such as those of the Appalachian region. As previously pointed out, the older oil-bearing formations are, as a rule, comparatively little disturbed - if any appreciable accumulations of petroleum remain in them. Thus, in petroliferous regions or fields of earlier age mud-volcanoes are generally lacking. In fact, it is doubtful whether true mud-volcanoes have ever been found in formations older than those of Tertiary age. It is in connection with formations of Oligo-Miocene age that they are most developed and frequent—indeed, even Eocene examples appear to be infrequent. Thus, their occurrence might be regarded as some token of the age of the formations wherein they are found, in new countries. In many Tertiary oil-bearing regions, however, they fail to occur, even where the folding is pronounced. Their absence may be regarded, where other indications and the conditions are favourable, as a promising sign, rather than otherwise—as tending to indicate lack of disturbance,

or a more or less intact character of the reservoirs. A noteworthy instance of the absence of mud-volcanoes in a Tertiary oil-region is seen in the oilfields of Dutch East Borneo, where the folding is very pronounced but without much disturbance or fracturing, the results being more or less reliable and lasting.

Mud-volcanoes often appear to be subject to periodical eruptions, with intervening periods of repose, or of practical extinction. Frequently their activity seems to awaken or increase after heavy rainfalls—in a similar manner as often seems to be the case in the appearance of seepages.

In many cases, violent eruptions or paroxysmal outbursts have been noted to take place, which are usually preceded and followed by intervals of quiescence, often of long duration. In the case of some of the mud-volcanoes of the Taman Peninsula in Russia, some noteworthy and violent eruptions have occasionally occurred, in which rocks and large quantities of argillaceous material are thrown up. A notable example of such mud-volcanoes is that of Waimata in the North Island of New Zealand, where periodical eruptions have spread around the vent large accumulations of mud, some ten acres in extent, at one time estimated to represent about 75,000 tons of extruded material*—in spite of the amounts that must be removed by the discharged water, rains, and streams. In one eruption, that occurred on July the 25th, 1906, the ejected material was thrown to a height said to have been of 250 to 300 feet. Likewise, in Trinidad, several such eruptions have from time to time taken place from the mud-volcanoes, notably in the cases of those of the "Devil's Woodyard" and the "Chemin du Diable." In the former locality several violent eruptions have been recorded from time to time

* *Mining Journ.*, June, 1910.

luring the last century, whereby rocks and mud were hrown up and sometimes the trees largely uprooted and elled—from which circumstance the Devil's Woodyard lerived its name. When this place was seen by the vriter, in 1917, it consisted of a barren patch, strewn vith ejectamenta of fragments from the subjacent ormation, with a few minor cones and emanations of ;as. In the other case named, rocks of large size are sometimes ejected, in violent outbursts which have been stated to recur about every ten or twelve years.*

Sometimes mud-volcanoes break out beneath the sea, and in some instances new islands have been created by such submarine eruptions, although to be eventually washed away by the sea, with more or less rapidity. Thus, a new island made its appearance off the Arakan coast of Burma, in 1907, which was reported to have been as large as about 1,200 by 600 feet in extent, with a height above the sea of about 20 feet, while a similar upheaval was observed as actually taking place, in the same region, by the commander of a mail steamer, in September, 1909.† In the same manner, a new island was formed off the southern coast of Trinidad, in 1912.‡ Another and remarkable instance of such occurrences is that of a new island which made its appearance on the north-western coast of Borneo, in lat. 5° 20′ 30″ N. and long. 115° 21′ E., off the shore of the Klias Peninsula, opposite Labuan, on September 21, 1897. This elevation was reported by residents at the time of its formation, as being about 600 feet in length and 450 feet in breadth, with an altitude of about 50 to 60 feet. This island was later visited and described by Prof. Carl Schmidt, who,

* Cunningham-Craig, E. H., "Oil Finding," p. 106.

† Handcock, A. R. W., *Geog. Journ.*, vol. xxxiv., No. 6, Dec. 1909, p. 690.

‡ Bosworth, T. O., *Geol. Mag.*, vol. ix., pp. 159-163, Dec. 5, 1912, "The Birth of an Island near the Coast of Trinidad (Mud-Volcano, Erin Bay)."

writing in 1904,* commented on the rapidity with which marine erosion was denuding the soft materials, and surmised that probably at the present time nothing would have remained of the island. When, however, the locality was visited by the writer,† in 1909, although more than half had been washed away, a considerable portion still remained, the hill measuring 210 by 120 feet in extent, and about 40 feet in height; but marine denudation was then rapidly and ceaselessly diminishing its size, so that it appeared as if it would not be long before it became completely demolished. It was then, however, no longer an island, having become joined to the shore, from which it was never very far distant, by accumulations of sand. The hill is called "Bukit Tumbo" (meaning hill that has "sprouted up"). It appears that this upheaval was synchronous with the occurrence of some seismic activity in the region. The following account by a resident at the time of the occurrence—Mr. Allard, who was in charge of some drilling operations in the neighbourhood, is of interest, as giving some description at the actual incidence:—"Halfway between Mempakal and Lambedan, on the 21st of September, in the afternoon, a small island was formed. Some natives were out gathering oysters, and noticed a good many bubbles rising, after which a gradual upheaval took place, and went on all night, forming a hill of about 200 yards by 150 yards, and 50 to 60 feet high. It seems to consist of nothing but slaty-looking clay, with a few sandstones in it, exactly similar to what we have been boring through. It is about 30 yards from the shore, and has evidently been forced up through rocks, as some large portions show where it has been scored and marked

* "Über die Geologie von Nordwest-Borneo und eine daselbst entstandene Neue Insel." Beitr. Geophys, Leipzig, 7, pp. 121-136, pl. vi. (Geol. map), 1904, and A.C.

† *Geog. Journ.*, vol. xxxvii., No. 1 (Jan., 1911).

by passing through some hard substance. There was a strong smell of gas when I went to see it on the 22nd, and on picking up some of the rocks they showed signs of a white waxy-looking substance having been forced into crevices, so I think this had been forced up by pressure of gas below. It is not far from where there are some oil-signs on the shore."

## (2) SOLID HYDROCARBONS AND BITUMENS.

It now remains to consider the solid and semi-solid or viscous hydrocarbons, or solid and semi-solid bitumens and asphalts—which may or may not constitute indications of petroleum, although they are usually the residual products or results of inspissation.

These substances range in physical state from that of a true solid to that of a viscous or semi-solid condition, while there are, of course, to be found all gradations passing from solid and viscous substances to a thick oil or maltha. Some bitumens, moreover, ordinarily solid, soften or liquefy when subjected to the heat of the sun. In colour, they vary from coal-black through brown, greenish and reddish-brown, to yellow, or sometimes colourless descriptions occur.

In the first place they may be divided into those of the non-paraffinaceous, or "asphaltic," class, and those having a paraffinaceous composition—or of the "cerous" description, as ozokerite.

Although the various descriptions of the former class are not always associated with petroleum, ozokerite is nearly invariably connected with the occurrence of oil—and that of a paraffin base.

Solid bitumens may be further classed, according to the mode of occurrence, as those existing in a comparatively pure or free state—or with little contamination

by intermixture with extraneous material, as in the case of the high-grade so-called "native" bitumens; and as impregnations.

Again, they are also to be distinguished as those of (1) superficial origin and accumulation—or that have solidified at the surface, and as those of (2) subterranean origin or "interstratal" occurrence—that have solidified or accumulated below. To the first-mentioned category (1) belongs the bitumen formed as the result of inspissation at or near the surface, from seepages or the outcropping of petroliferous beds, such as is commonly known as "asphalt." Such bitumen or asphalt seldom occurs in a quite pure condition, being usually intermixed with mineral and other matter to a greater or less extent, while there may be a predominance of bitumen or the reverse. In the case of the asphalt of the Trinidad Pitch Lake, for example, the material consists of a predominance of bitumen, together with a considerable amount of mineral matter—about 35 per cent. (on the average). Although asphalt sometimes occurs in a comparatively or very pure condition (sometimes as such on a large scale), as, *e.g.*, notably in the case of that of Bermudez, Venezuela, as also in the case of that found in the Dead Sea.

To the other category (2) generally belong the various forms of the purer, and high-grade, solid bitumens, or the so-called "native" bitumens, which generally occur within the rocks, as infillings of fissures (such as those associated with faults, slip-planes or joints, or in between bedding-planes), where they have been formed or solidified. (A name is wanting in order to describe, and distinguish from the asphalt class, all the solid bitumens of this character, although the term "meta-asphalt" was suggested for this purpose a long time ago, but has not since been generally used, while also the term of "asphal-

tite" has been employed to denote those types of solid bitumens that fuse at a temperature of above 250° F. The writer would suggest the name "bitumenite"* for the distinction of such occurences of solid bitumens.)

Impregnations are principally represented by the asphaltic rocks or limestones, such as, *e.g.*, the Val de Travers limestone, as also asphaltic sandstone, sand, and earth; in which bitumen is intermingled with or constitutes an intimate ingredient of the rock. Another description of impregnation, however, may arise on the surface from exudations of oil or seepages permeating superficial deposits, such as sands or earthy material, thus forming asphaltic deposits—although in this case there is often a predominance of bitumen over the mineral material. Of such a nature are the asphaltic patches or "black spots" common in most petroliferous regions.

Unfortunately, the words "bitumen" and "asphalt" are employed with various meanings and applications, and considerable ambiguity and confusion has arisen in their usage, as also in the case of the names "pitch," "tar," and others. Thus the term "bitumen" is often confined to the solid bituminous substances—while the adjective "bituminous" is frequently used to describe pyro-bituminous rocks. The term "asphalt," in commercial usage, is commonly employed to denote the artificial preparation—rather than the natural rock or substance. Moreover, it is sometimes invested with a chemical signification—as in speaking of oils of an "asphalt base" (for petroleum which is not of a paraffin base, or paraffinaceous), or as a general title for the distinction of the bitumens other than those containing paraffins. While the term "asphaltite" has been introduced in order to define certain groups of solid

* This term, however, was proposed by Prof. Traill, in 185?, for designating "Torbanite," but has not been subsequently used for this purpose.

bitumens (the higher grade types) characterized by comparatively high fusing-points. Likewise, the word "pitch" is often employed to denote solid bitumen or asphalt, as also the name "tar" is sometimes used to describe viscous petroleum or "maltha," when these terms should properly mean the products derived from coal-tar. Although the terms "mineral pitch" and "glance-pitch" are sometimes, and can be, employed to signify solid bitumens; as likewise the term "mineral tar" is sometimes used—to signify viscous oil or "maltha."

The term "petrolite" has been introduced for distinguishing, in a general manner, and including all the forms of the solid bitumens.

As regards the definition of the term "asphalt," some distinguish "asphalt" from the other or high-grade descriptions of solid bitumens as that having a low fusing-point, in distinction to those types that have high fusing-points—over 250° F., and that are infusible—termed "asphaltites" and "asphaltic pyrobitumens"* respectively. The writer, however, prefers a differentiation based on the geological mode of occurrence—*i.e.*, as of superficial, or of subterranean—or "inter-petrean"—occurrence and origin.

But, as previously pointed out, the term bitumen† is here used in the widest sense—as would appear to be in accordance with the derivation or original Latin application of the term, to comprise all the natural hydrocarbons, whether solid, liquid or gaseous, excluding, of course, the substances belonging to the carbonaceous series and pyrobitumens.

Sometimes the name "petroleum" is applied in this generic manner, to embrace all the forms of bitumen in connection, although the use of the word—in accord-

* H. Abraham, "Asphalts and Allied Substances" (1918).

† Taken from the Latin word "bitumen."

ance with its literal meaning—should properly be limited to the liquid descriptions.

The expression "natural hydrocarbons" is generally understood to imply all the bitumens, or the "bituminous series," although this heading is sometimes also taken as comprising the coals, when such hydrocarbons are divided into (1) the Carbonaceous Series and (2) the Bituminous Series.

The coals, however—while essentially consisting of carbon and hydrogen—are, in general, more highly oxygenated substances than the bitumens, although some bitumens, and the inspissated products, may have a considerable oxygen content. But anthracite coal, on the other hand, consists mostly of carbon. The bitumens, moreover, are generally characterized as being substances rich in hydrogen, and consequently containing larger amounts of volatile hydrocarbons.

It is difficult, however, to draw any hard and fast line between bitumen and coal, or between the bituminous and the carbonaceous series, the one group grading through various forms into the other; some forms which occur having occasioned controversy—and even given rise to litigation—as to whether such should be classed as a coal or as a bitumen, as, *e.g.*, in the case of some solid bitumens or allied substances, found in New Brunswick, Canada, and Indiana (U.S.A.). In this manner there is a gradation from the bitumens—through grahamite and the asphaltic pyrobitumens—to the pyrobitumens.

It is, however, the geological conditions and environment, as also the apparent origin, of the occurrences, that generally afford some indications and the best basis for distinguishing whether the substance is of the nature of a coal or otherwise—the coals proper being directly the residual products of the accumulation and

decomposition of plant-debris, as also as to whether there is any present, past, or possible connection with petroleum. The coals, moreover, have been more specifically differentiated—on a chemical basis—as being substances possessing cellulosic residue, which on distillation can produce phenols.

As regards the uses, or misuses, and interpretations of the term "bitumen," which, as already observed, has been, and is, employed with different meanings and limitations, the word being frequently confined to the solid substance, it is found that various definitions of bitumen, or opinions as to the application of the word, have been given by different authorities, while it is often vaguely defined. For instance, the term "bitumen" is defined by various writers, or in some encyclopædias, respectively as "a pitchy, inflammable substance," or "a mineral substance of a resinous nature and highly inflammable" and having a "pitchy odour," and again as applying "to liquids or solids which fuse at a low temperature, give off a characteristic strong smell, and burn very readily, leaving but little carbonaceous residue." * Or, again, another definition describes bitumen "as a rock, sometimes solid but sometimes viscous," such being named accordingly "asphalt" and "pissasphalt." † Some even have imposed a definite thermal melting-point—such as not less than 35° C.—in the specification of bitumen.

Such definitions are obviously vague and inappropriate, as also inaccurate—while it is seen that they generally relegate the term "bitumen" to the solid substance.

Other authorities, however, have recognized solu-

* Thenard, L. J. (Baron), "Traité de Chimie," vol. v., p. 240 (1836).

† V. Urbain and E. Stanislas Meunier in "Encyclopédie Chimique" (M. Fremy), tome ii. Complément, 1re Partie ("Combustibles minéraux"), Chap. vii., p. 410 (1885).

bility—or partial solubility—in such solvents as carbon disulphide, petroleum spirit, ether, turpentine, and chloroform, as characterizing a true bitumen—although such a definition would exclude some bituminous occurrences—which have been termed the "Kerites," these being generally regarded as belonging or allied to the bitumens.

In a classification and suggested nomenclature for bitumen, pitch, and asphalt, given by A. Danby,† the following definition and description for the bitumens and asphalts are given, the latter designation being applied to impregnations—artificial as well as natural, and the former to the purer substance—or that "mixed" with some impurities or containing some amount of extraneous matter, thus :—

"*Bitumens.*—All such substances which are found in Nature and require no further treatment other than the extraction of the mineral and vegetable impurities that they may have mixed among them; which are completely soluble in carbon bisulphide, but only partially so in ether, and almost completely insoluble in alcohol. Under this heading are ranged the bitumens obtained from Trinidad, Venezuela, Cuba, Mexico, etc., Barbadian '*manjak,*' glance-pitch, grahamite, gilsonite, elaterite, wurtzilite, Syrian asphalt, maltha, goudron mineral, bergteer, the asphalt oils, and the viscous or solid bitumen that is found impregnating rock asphalt.

"Also such substances which are derived from the distillation of any of the above or of the asphaltic petroleums.

"*Asphalts.*—All such substances that are impregnated —as distinct from being merely mixed—with either bitumen, pitch, or a mixture of the two. The impregna-

* *Cf.* C. Richardson, "The Modern Asphalt Pavement," p. 107 (1905).
† "Natural Rock Asphalts and Bitumens," p. 7 (1913).

tion condition is necessary so as to clearly distinguish such bodies from impure bitumen, by which, as has just been mentioned, mixtures are designated. The minerals usually forming the base of asphalts are limestone or sandstone, though, in the artificial types, other pulverised materials are often used. It would, indeed, be preferable if only the naturally impregnated rock were alluded to under this name, but certain terms, such as 'British asphalt,' which refer to essentially artificially-formed products, have now such a definite technical meaning, that to exclude them from this heading would be at least undesirable, as causing that very looseness of expression and description that it is so necessary to avoid, even if such exclusion were not actually impossible.

It is difficult, or impracticable, however, to distinguish "impregnations" from mixtures, the latter generally arising from impregnations. The same writer further groups the bitumens into the subdivisions of "bitumens proper" for the solid types, and "maltha" for the viscous or semi-fluid descriptions, as likewise pitches are subdivided into "pitches proper and tars;" while "asphalts" are merely divided into "natural" and "artificial" asphalts.

A more appropriate definition of bitumen is the following, as given by the "American Society for Testing Materials":—"Bitumens are mixtures of native or pyrogenous hydrocarbons and their non-metallic derivatives, which may be gases, liquids, or solids, and which are soluble in carbon disulphide."

The following definition of the term "Bitumen" is given by H. Abraham,* and is one that should be generally acceptable (except for the exclusion of the infusible and insoluble varieties):—"A generic term

* "Asphalts and Allied Substances," p. 21 (1918).

applied to native substances of variable colour, hardness, and volatility, composed of hydrocarbons substantially free from oxygenated bodies, sometimes associated with mineral matter, the non-mineral constituents being fusible and largely soluble in carbon disulphide, and whose distillate fractioned between 300° and 350° C. yields considerable sulphonation residue," adding a note that the definition "includes petroleums, native asphalts, mineral waxes, and asphaltites."

It is evident, then, that some sort of revision in the nomenclature, or rearrangement in the terminology, in respect of the bitumens and the solid hydrocarbons, is to be desired.

The word "petrolite" has been introduced to distinguish, and to comprise all, the solid forms of bitumen. But, as previously pointed out, a further word is needed, in order to distinguish the purer or high-grade and more highly mineralized bitumens—usually of subterranean origin and solidification—from the types of the nature of common asphalt (although the term "meta-asphalt was proposed by Dr. Taylor, of Philadelphia, for this purpose, a long time ago, but does not seem to have ever come into use. The term "bitumenite" is suggested in this connection).

The term "asphaltite," however, has been employed by H. Abraham,* in order to distinguish such bitumens as gilsonite, glance-pitch and grahamite, as are characterized by high fusing points (over 250° F.); the infusible varieties, such as elaterite, wurtzilite, albertite, impsonite, etc., being classed under the designation of "asphaltic pyrobitumens."

Bitumen, and the natural hydrocarbons, may be broadly grouped as follows—in a general manner :—

* "Asphalts and Allied Substances," p. 148 (1918).

## Natural Hydrocarbons.

| Bituminous Series. | | | | Carbonaceous Series. |
|---|---|---|---|---|
| Solid. | Viscous or semi-solid. | Liquid. | Gaseous. | |
| (*Petrolites*).<br>(1) Asphalt.<br>(2) ("Bitumenites"), the various or purer forms of solid bitumens (meta-asphalts), (including "asphaltites" and "asphaltic pyrobitumens," and "Kerites").<br>(3) Ozokerite, and the paraffinaceous class. | Maltha (Piss-asphalt)<br>Elaterite. | Petroleum (Asphaltic, paraffinaceous and mixed-base oils). | Natural and petroleum gases. | |

The following is another classification, which has been given by Dr. W. P. Blake :—*

| | | | | |
|---|---|---|---|---|
| Hydrocarbons. | Bituminous | Gaseous | | Marsh gas<br>Natural gas |
| | | Fluid | | Petroleum (Naphtha) |
| | | Viscous and semi-solid | | Maltha<br>Mineral tar<br>Brea, Chapopote |
| | | Elastic | | Elaterite<br>Wurtzilite |
| | | Solid | Asphaltite | Albertite<br>Grahamite<br>Uintaite |
| | | | Coal | Bituminous coal<br>Semi-bituminous coal<br>Anthracite coal |
| | Resinous | | | Succinite (amber)<br>Copalite<br>Ambrite, etc. |
| | Cerous | | | Ozokerite<br>Hatchettite, etc. |
| | Crystalline | | | Fichtelite<br>Hartite, etc. |

* *Trans. Amer. Inst. Min. Eng.*, vol. xviii., p. 582 (1890).

To revert to the consideration of the various types of the "native" solid bitumens, these have received various names—some according to the locality of occurrence, some according to the local native name for the mineral, and others after persons who have been identified with them; while they differ in relative purity or amount of intermixture with extraneous material, chemical composition, behaviour in solvents, and physical properties—such as relative hardness and softness, tendency to viscosity or fluidity, and fusibility. Generally their specific gravities slightly exceed unity, with the exception of ozokerite (or the cerous descriptions).

The solid bitumens are mostly soluble, to a greater or less extent, in turpentine and chloroform, and partly soluble in petroleum spirit, benzol, and ether, and are all more or less dissolved by carbon disulphide, with the exception of those termed "Kerites," which also are mostly infusible, this group of substances being generally regarded as being allied or assignable to the bitumens. They are generally insoluble in alcohol.

In connection with the solid bitumens, the term "petrolene" is used to denote the volatile portion that can be distilled off,* the term "asphaltene" being given to the non-volatile constituents — or residue.

Here again, however, there is ambiguity in the nomenclature, as the term "petrolene" is also employed to denote the percentage soluble in petroleum spirit, ether, or acetone, and likewise the term "asphaltene" for the insoluble portion or residue thereof. Again, the latter term is also sometimes used to signify the fraction dissolved by turpentine or chloroform. The term "malthenes" is sometimes substituted for "petrolene" in

* Sometimes specified as that which is volatile at 325° F. C. Richardson, "The Modern Asphalt Pavement," pp. 117-118, New York (1905).

this latter sense—*i.e.*, for the soluble content, in view of the differing meanings.*

In commercial usage, however, either application of the term "petrolene" amounts to much the same thing—for practical purposes. The commercial value of a solid bitumen is sometimes reckoned according to the percentage of petrolene—especially for such purposes as the manufacture of varnishes, etc.

That which has been termed the "carbene" content, in a solid bitumen, is the portion that is soluble in carbon disulphide, and insoluble in carbon tetrachloride

Some occurrences of solid bitumens are directly or obviously connected with petroleum, and in other cases the relationship is obscure or remote, while some examples would appear to have no such connection, or to be of independent occurrence

It is, however, amongst petroliferous strata that they most commonly occur, as infillings of fissures —fault-planes, joints, or sometimes along bedding-planes, etc., usually in argillaceous strata, although in some cases found in limestones.

Among the several varieties of solid "native" bitumens —or "bitumenites"—that have been distinguished or received names, the following are the principal types, or names, that have been recognized.—

Manjak (after the Barbadian name), or "Glance Pitch."
Uintaite (named after the Uinta Mountains or County, Utah, U.S.A.). Also termed "Gilsonite" (after S H Gilson).
Tabbyite (named after the Tabby Canyon, Utah, U.S A.)
Piauzite (named after Piauze, Carniola Prov, Yugoslavia).
Grahamite (named after the Messrs Graham).
Elaterite (Mineral "Caoutchouc")
Coorongite (named after the Coorong District, South Australia).
Wurtzilite (named after Dr. Henry Wurtz).
Albertite (named after Albert County in New Brunswick, Canada), also "Melan-asphalt" and "Wetherlite" (after Dr. C. M. Wetherill).

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* As proposed by Prof. C. Richardson, who also characterizes the term "Asphaltenes" as the non-volatile hydrocarbons soluble in carbon tetrachloride. *Ibid*, p. 117. *Cf.* also D. Holde, "The Examination of Hydrocarbon Oils," etc. (Translation), New York, 1922.

Nigrite ("Niger"—black).
Impsonite (named after the Impson Valley, Oklahoma, U.S.A.).
Ozokerite (after the Greek "ὄζειν"—"emit odour," and "κηρος"—"wax"), ("Mineral-wax"), and the substances belonging to the "cerous" or paraffinaceous class, as, *e.g.*, Neft-gil, Hellenite, Scheererite, Könlite, Hatchettite, Hartite, Dinite, Fichtelite, Zietrisikite, Napalite, Kabaite, etc.

Of these varieties of solid bitumens the first-mentioned substances, down to Grahamite, are fusible, as also the Ozokerite and paraffinaceous class, although Grahamite is with difficulty fusible; while the other descriptions named (without Ozokerite, etc.), from Elaterite to Impsonite inclusive, represent infusible types—although some of them dissociate on heating, or are fusible after decomposition.

Some primarily class these minerals (other than those of the Ozokerite description or containing paraffins) into the fusible types—or rather those the fusing-points of which are over 250° F., under the heading of "asphaltites," and into the infusible descriptions—which have been styled "asphaltic pyrobitumens." This latter term, however, is somewhat inappropriate and misleading for describing these bitumens, although they are sometimes excluded from the bituminous series and classed with the pyrobitumens; but they are obviously more closely related to the bitumens—in any case in their mode of occurrence and origin—than to the pyrobitumens proper—which comprise the coals and shales, while, moreover, appearing often to have resulted from the metamorphosis of the other descriptions of bitumen—as also from petroleum itself.

Some, again, class those varieties which are insoluble in carbon disulphide under the designation of "Kerites." The infusible descriptions are, however, generally insoluble—or only to a fractional extent soluble—in that solvent, and thus for the most part correspond to the "Kerites."

As regards the "asphaltites," moreover, it is, as pre-

viously pointed out, hardly practicable to impose the restriction of any definite fusing-point for their distinction, or to draw any hard and fast line between the bitumens fusing above or below 250° F., as the fusibility in the same occurrences or seams may vary, the melting-point frequently becoming lower at greater depths—as instanced in the case of some of the "Manjak" seams found in Barbados.

| | Streak. | Specific Gravity at 77° F. | Fusibility. | Fixed Carbon. Per cent. |
|---|---|---|---|---|
| ("Asphaltites") Uintaite (Gilsonite). | Brown | 1·05-1·10 | 250°-350° F. | 10-20 % |
| Glance-Pitch (including "manjak"). | Brown to black | 1·10-1·15 | ,, | 20-30 % |
| Grahamite, | Black | 1·15-1·20 | 350°-600° F. | 30-55 % |
| ("Asphaltic Pyrobitumens") Elaterite, | Light brown | 0·90-1·05 | Decomposes | 2-5 % |
| Wurtzilite, | ,, | 1·05-1·07 | ,, | 5-25 % |
| Albertite, | Brown to black | 1·07-1·10 | Fusible only on decomposition | 25-50 % |
| Impsonite, | Black | 1·10-1·25 | Infusible and decomposes | 50-85 % |

As adopted in the system of classification employed by H. Abraham,* the fusible bitumens, or "asphaltites," are arranged or classed according to three principal types or classes—namely, those of "Gilsonite," "Glance-Pitch"—including "Manjak," and "Grahamite," mainly on the basis of the degree of fusibility, specific gravity,

* "Asphalts and Allied Substances," pp. 127 and 149; and Eighth International Congress in Applied Chemistry (Sept. 1912).

and amount of fixed carbon possessed by the substances. While the infusible varieties, or "asphaltic pyrobitumens" are likewise assigned to four main types—namely, "Elaterite," "Wurtzilite," "Albertite," and "Impsonite," on a similar basis—principally according to the specific gravity and percentage of fixed carbon present in the minerals; as in the manner distinguished in the table on the previous page.

It is difficult, however, to assign all the various occurrences and descriptions, or make their physical and chemical properties conform, to such specific types, or to individual occurrences, the several varieties and occurrences each having particular characteristics, as also their geological mode of occurrence and environment, which should be taken into account.

There is, moreover, much variability in individual occurrences, and it is probable that exploration downward would, in many cases, reveal a gradual change in the properties of the substances—such as fusibility, percentage of fixed carbon, specific gravity, etc.; while the several types appear to represent but stages in the process of metamorphosis of bitumen—which may proceed from liquid petroleum to the most refractory solid bitumen.

Another proposed method or system of classification of the "petrolites," on a chemical basis, has been formulated by J. E. Hackford,* as follows :—

| | | |
|---|---|---|
| ASPHALTITES | Oxy-asphaltites | Oxy-aliphatic asphaltite.<br>Grahamite.<br>Oxy-aromatic asphaltite.<br>Macuspana seep.<br>Oxy-hetero-cyclic asphaltite.<br>Russian seeps (solid). |
| | Thio-asphaltites | Thio-aliphatic asphaltite.<br>Gilsonite. Manjak.<br>Thio-aromatic and thio-hetero-cyclic varieties are at present unknown. |

* Hackford, J. E., "The Significance of the Interpretation of the Chemical Analysis of Seepages," *Journ. Inst. Pet. Tech.*, vol. viii., pp. 201 (1922).

| | | |
|---|---|---|
| KERITES | Oxy-kerites | Oxy-aliphatic Kerite.<br>Elaterite and Albertite.<br>Other two classes unknown. |
| | Thio-kerites | Thio-aliphatic Kerite.<br>Wurtzilite and Impsonite.<br>Other two classes unknown. |

The asphaltites and kerites (insoluble) are here primarily subdivided on the basis of being "oxy" or "thio" —*i.e.*, mainly according to the amount of the sulphur content. This differentiation does not, however, apply very well to the various occurrences; while, moreover, "manjak" is characterized by its exceptionally low sulphur content, whereas some examples of grahamite, as, *e.g.*, that of Trinidad and Oklahoma, have a high sulphur content.

**Manjak.**—Manjak is the name given to the solid bitumen, or glance-pitch, occurring in veins and fissures, in the island of Barbados. The same name, however, is also used to describe the similar occurrences in Trinidad, although this bitumen is of a somewhat different nature.

The Barbadian manjak, although variable in quality, is generally very pure, with comparatively little intermixture of extraneous mineral matter or other impurities, and furnishes some of the highest-grade solid bitumen known, and the superior qualities, which are rich in petrolene, fetch a high price, the material being much used for the manufacture of varnishes, japans, etc.

This mineral is evidently and intimately connected with petroleum. It occurs in veins or seams, infilling fissures —such as those connected with faults, joints, minor slip-planes, or bedding-planes, which traverse the Tertiary argillaceous strata at all angles.

It is black in mass, but shows a dark-brown streak, and the fracture is conchoidal.

The material is usually of higher grade and richer in

petrolene in the centre of the seams, as also deeper down, than at the outer parts.

In typical samples the specific gravity is in the neighbourhood of 1·10 (at 77° F.), and the percentage of fixed carbon is from 25 to 30, while the fusing-point is generally about 350° F., but at depth the fusing-point of the substance often becomes lower, while sometimes the material is found even to merge into a maltha—as traced downwards along the seam.

In the flame it softens, splits, and burns. The sulphur content is very small—about 0·7 to 0·9 per cent It is almost completely soluble in carbon disulphide and partially soluble in benzine, turpentine, and ether, but insoluble in alcohol.

The Trinidad manjak partakes more of the nature of a grahamite, having a higher fusing-point (350°-440° F.), also a higher specific gravity and percentage of fixed carbon, and a hackly fracture ; it is of a more indurated and usually less pure description—having generally a greater intermixture of extraneous mineral matter.

At deeper levels, however, the fusibility declines—the fusing-point being down to 280° F. in the soft material in the centre of the vein at the 200-foot level in the mine —and at depth a variety is found in the interior of the seams, with a conchoidal fracture, which is more of the nature of a "glance-pitch." Also a variety with a columnar structure occurs, in the exterior parts of the seams, having columnar jointing which runs at right angles to the margin of the vein.

Other deposits of "glance-pitch," similar to the Barbadian manjak, are found in Colombia (South America), where deposits are worked at Chaparral, in the Province of Tolima, on the Saldaña River (a tributary of the Magdalena River), which locality is situated about 100 miles to the south-west of Bogota ; in Hayti, near Azua,

on the Bay of Ocoa; and also in the Arabian desert, in the neighbourhood of Neapolis; while extensive deposits occur in Syria (Hasbeiya). Some of the solid bitumen, moreover, found floating on the water in the Dead Sea has a high fusing-point (about 275° F.), and would be described as a "glance-pitch," this being supposed to be derived from veins occurring at the bottom of the Dead Sea.

**Uintaite** or **Gilsonite**.—Uintaite is, like the Barbadian manjak, one of the purest occurrences of solid bitumens, as also one of the most valuable, but differs from "manjak" in its brown streak and slightly lower specific gravity; also in having a smaller percentage of fixed carbon.

The fusing-point is more or less similar to that of "glance-pitch" or "manjak," being from 250° to 350° F., while the specific gravity is about 1·05 to 1·10 (at 77° F.), and the percentage of fixed carbon runs about 10 to 20. It is black in mass, but the streak is brown, and has a conchoidal fracture, with a brilliant lustre. It is soluble in carbon disulphide and ether, dissolves in turpentine, and is largely soluble in chloroform and petroleum spirit, but is insoluble in alcohol. The substance has the property of becoming electric on friction. The sulphur content ranges about 1·7 to 2·0 per cent.

Gilsonite, or Uintaite, is found only in a comparatively restricted area, which lies partly in Eastern Utah (Uinta County) and partly in Western Colorado, the mineral being principally found in the area known as the "Uinta Basin," and is mined in the neighbourhood of the confluence of the Green and White Rivers.

The mineral occurs in a number of vertical and more or less parallel veins, varying in thickness from a fraction of an inch to several feet, which traverse the Tertiary shales and sandstones in a north-westerly to south-

easterly direction. The grade of the material is fairly uniform in all the veins, although, as is usually the case in "bitumenites," it is of a better quality in the centre of the vein than at the margin, where the fracture may be semi-conchoidal with only a semi-bright lustre. As frequently occurs in asphaltites, a columnar or pencillated variety is found in the exterior regions of the seams."

Gilsonite is one of the most valuable native bitumens, and is largely used for the manufacture of paints, varnishes, japans, etc. The mineral evidently has affinities with petroleum.

The name "Courtzillite" has been given to a variety of Uintaite

**Tabbyite.**—This name has been applied to a pure solid bitumen of low fusibility, found in the Tabby Canyon, which is a branch of the Duchesne River, in the Uinta County, Utah; this locality lies about 8 to 9 miles south-west of the town of Theodore, and about 30 miles west of the town of Duchesne. It has a conchoidal fracture and bright lustre, with a black streak. The fusing-point is about 178° F., the specific gravity is slightly above unity, and it gives a percentage of fixed carbon of about 9. It is nearly completely soluble in carbon disulphide and largely soluble in petroleum spirit, and contains about 2 per cent. of sulphur.

**Piauzite** is a fusible solid bituminous substance found, associated with brown coal, at Piauze, near Neustadt, in Carniola, and also on Mount Chum, near Tüffer, in Styria, Austria. It has a brownish or greenish-black colour in mass, and a light brown streak; the specific gravity is about 1·22. It is soluble in ether, caustic potash, and partially so in alcohol, and fuses at about 315° F.

**Grahamite.**—The Grahamites are in the main distinguished by having a relatively high specific gravity, a high fusing-point, a large percentage of fixed carbon, and a black streak, while they are more or less soluble in carbon disulphide. Their general characteristics are represented by blackness in mass and streak, a conchoidal to hackly fracture, with bright to dull lustre, and they have a specific gravity of from about 1·15 to 1·20 (at 77° F.), and a fusing-point of about 350° to 600° F., the amount of fixed carbon ranging from 30 per cent. to about 55 per cent. They are largely to completely soluble in carbon disulphide (from 50 to 100 per cent.) and in chloroform, and partially soluble in petroleum spirit and turpentine, but insoluble in alcohol.

They more frequently occur in a less pure condition than the other "asphaltites," and in some cases may contain up to 50 per cent. of extraneous mineral matter; while often found in thicker veins. They are generally connected with the occurrence of petroleum.

The original Grahamite occurs, and was mined, in West Virginia, at a locality in a branch of the Hughes River, in Ritchie County, situated about 25 miles south-east of Parkersburg, having been named after the Messrs. Graham, who were interested in that mine; and the substance was originally described by Dr. Henry Wurtz. The mineral there fills vertical fissures that traverse the Carboniferous sandstones and shales, the veins ranging from about 5 feet down to a few inches in thickness.

Other occurrences were subsequently discovered and recognised to be similar to Grahamite, in the United States and elsewhere.

Several deposits occur in Oklahoma, including the largest known vein of solid bitumen in the world, which is found in the Jackfort Creek, the locality being situated

about 12 miles west of Tuskahoma; it has a thickness of from 19 to 24 feet, and extends for about one mile in length. Another large deposit, which has been mined, occurs in the Impson Valley—about 16 miles to the north-west of Antlers, Oklahoma.

Other occurrences of the character of Grahamite are found in Colorado, Texas, in several districts of Cuba—in the provinces of Havana, Pinar del Rio, and Santa Clara (where it is found associated with serpentine), and in Mexico—in the provinces of Tamaulipas and Vera Cruz (in the Huasteca, on the Panuca River). The occurrence in Trinidad has already been described under "manjak."

The sulphur content in Grahamites is often high—from about 3 per cent. up to over 7 per cent. in some instances, although in the case of the original occurrence, in West Virginia, it is only about 1·8 per cent.

Grahamite might be regarded as affording a sort of connecting link between the fusible bitumens or "asphaltites" and the infusible and insoluble types, which now come to be considered.

**Elaterite.**—Elaterite, although comparatively soft and of an elastic character—hence the name of "mineral caoutchouc"—is one of the infusible and insoluble bitumens ("kerites" and "asphaltic pyrobitumens"), but it is fractionally soluble in ether (about 18 per cent.). It has a dark-brown colour in mass, is sub-translucent, with a light-brown streak, and has the property of being somewhat elastic and compressible. It has a very small percentage of fixed carbon—only about 2 to 5 per cent., and the specific gravity approaches unity.

The original elaterite is found in lead-mines in Derbyshire—in the Odin mine, near Castleton (having been discovered and described by Lister in 1673), where it occurs, associated with the galena and calcite, in

reniform and fungoid masses, in the Carboniferous Limestone.

Other similar occurrences are reported in Scotland—*e.g.*, in the Chapel quarries in Fifeshire; in the coal-mine of Montrelais (near Varades, in the Loire Inférieure), in France; near Neuchâtel, Switzerland, and in the island of Zante.

It is of scientific interest only,* while the relationship with petroleum is somewhat obscure. It is, however, really a prototype of wurtzilite.

Deposits of a solid bitumen analagous to elaterite have been found in the neighbourhood of Lake Balkash, in the Province of Semiretchensk (Siberia), near the mouth of the Ili River. This is fairly pure, having only 3 to 5 per cent. of extraneous mineral matter; it has a specific gravity of 0·995, and is very slightly soluble in carbon disulphide.

**Coorongite,** which has been classed as a variety of elaterite, is the name given to a curious bituminous deposit found in the Coörong district, south of Adelaide in South Australia (already mentioned in Chapter II.).

**Wurtzilite.**—The true wurtzilite is of a somewhat restricted occurrence, being only found in a comparatively limited area (about 100 square miles in extent), which is situated in the basin of the Uinta River, in the district of the Strawberry Creek, Utah, and about 50 miles west-south-west of Fort Duchesne.

This mineral is found in a fairly pure condition, and is black in mass, with a light brown streak, and, like elaterite, it is of a fibrous nature and elastic—being flexible in thin flakes; while it is sectile, and the fracture is conchoidal, with a bright lustre.* It is, likewise, one of the infusible (or rather it does not fuse

* *Cf.* Blake, W. P., *Trans. Amer. Inst. Min. Eng.*, vol. xviii., p. 497 (1890).

without decomposition) and insoluble bitumens, although a fractional amount (about 5 to 10 per cent.) is soluble in carbon disulphide. But, on being heated, wurtzilite dissociates or depolymerizes, in this way forming fusible and soluble products. The percentage of fixed carbon is also low, being from 5 to 25 per cent., and the specific gravity (at 77° F.) is about 1·06. The sulphur content is high.

The mineral occurs in comparatively thin and nearly vertical veins, which traverse a shaly limestone, of early Tertiary age.

It also has been termed " Ægerite " and " Æonite."

**Albertite.**—The original albertite occurs in the Lower Carboniferous shales of New Brunswick (Canada), at a locality in Hillsborough County, about 20 miles south of Moncton, not far from the Albert Mines, whence it takes its name. It was formerly mined there, having been used along with coal for the production of gas, and at first was even regarded as being of the nature of coal (having been termed " Albert coal "), although geological examination and the mode of occurrence showed that the mineral could not be of the character and origin of coal, since it occurred in veins intersecting the strata. It was, moreover, subsequently examined by Dr. Wetherill, who showed that the mineral differed in chemical and physical properties from any of the coals, being more allied to asphalt or bitumen, and he named it " melanasphalt."

Subsequently, occurrences of substances which were found to be of a similar character were discovered elsewhere, and the name " albertite " has become more or less a generic term for such infusible and insoluble bitumens as are of a similar description to the original New Brunswick mineral.

In general, the characteristics of the Albertites are determined by (1) infusibility (but with dissociation, or partial

depolymerization, on heating); (2) insolubility in carbon disulphide, etc.; (3) a specific gravity of about 1·07 to 1·1 (at 77° F.); (4) a comparatively high percentage of fixed carbon, ranging from 25 to 50 per cent.; and (5) a small percentage of oxygen—which is less than 3 per cent.

The appearance in mass is usually of a brilliant black description, while the streak is brown to black. The fracture is conchoidal to hackly, with a bright lustre. The Albertites are only fractionally soluble (about 2 to 10 per cent) in carbon disulphide and but sparingly soluble in petroleum spirit (up to about 2 per cent.). The substance has the property of becoming electric on friction. The sulphur content is usually low, being about 1 per cent.

In the New Brunswick occurrence, in Hillsborough County, the mineral occurs in vertical and steeply inclined veins, from a fraction of an inch to a maximum of about 17 feet in thickness, traversing bituminous shales of Lower Carboniferous age, which abound in fossil fishes. This occurrence takes the form of one principal fissure-vein with smaller lateral veins and ramifications.

An occurrence of solid bitumen, reported to be an albertite, is found in the locality of Libollo, in Angola, Portuguese West Africa, and so has received the name of "Libollite." *

A solid bitumen, which has been described as an albertite in character, is found occurring in small veins in the shales of the Old Red Sandstone, and also in the underlying gneiss, near Strathpeffer, in Ross-shire.

"*Tasmanite,*" which occurs in small grains disseminated in a pyrobituminous shale, in Tasmania, near the Mersey

* Gomes, Comm. Dir. Trabalhos Geol. Portugal, iii., pp. 244-90; iv., p 206 (1896-8).

Impsonite is of a dull black appearance in mass, and somewhat brittle, with a hackly fracture and semi-dull lustre, and the streak is black. In the flame the substance decrepitates. Some specimens have up to about 5 per cent. soluble in carbon disulphide, and others only a trace soluble. The sulphur content is not generally high (between 1 and 2 per cent.).

The deposit in the Impson Valley, Oklahoma, U.S.A., from which the name is derived, was found to be more of the character of a "grahamite"; but a large deposit of "Impsonite" is found in South-Eastern Oklahoma at a locality, in the La Flore County, situated on the southern slopes of the Black Fork Mountain, about two miles to the east of Page, where it fills a fissure due to a fault, the vein being about 10 feet in thickness, traversing a series of sandstones and shales of Carboniferous age. It is also found at another locality, over the border, in Arkansas, situated at a distance of about 12 miles to the east of the above mentioned deposit in the Black Fork Mountain, occurring as veinlets in sheared shales and sandstones, also of Carboniferous age; while another occurrence has been found in Oklahoma, in the Murray County, situated at about 5 miles to the north-east of Dougherty Also a deposit has been reported to be found in Nevada, U.S.A., at a locality in the Pine Creek Valley, in Eureka County, situated about 15 miles to the south of Palisade, where it occurs in a vein, which is over 300 feet in length, the substance filling fissures in a series of fractures in steeply inclined sandstones and shales of Carboniferous age.

This concludes the consideration of the solid non-paraffinaceous bitumens—or "bitumenites."

It will have been noticed that the majority of the occurrences or types of these solid bitumens are described

or reported as found in America, and particularly have many descriptions and varieties been found and distinguished in Utah—which might indeed be regarded as furnishing a sort of museum for the types of solid bitumens or "bitumenites." This is not, however, so much on account of there being more different species or more numerous occurrences in America, as owing to the circumstance that in that country they have been more studied, examined, and differentiated.

It is probable that the several types are to be found in many countries or occur in most petroliferous regions, but remain to be recognized, or determined by examination.

Moreover, it is probable that the contained bitumen in many cases of the so-called "asphaltic" rock-impregnations may often be of the description of one of these classes of solid refractory bitumens or "bitumenites"; thus, in the case of some occurrences of bituminous grits found in Trinidad, the bitumen contained in the interstices is of high fusibility.

But, as previously mentioned, these several types of solid bitumens more or less illustrate progressive stages in the metamorphosis of bitumen; although the character and differences in the chemical composition of the original bitumen or petroleum, from which they resulted, may in some measure determine the varieties and characteristics, the environment and physical conditions under which they solidified and underwent metamorphosis being also a factor in their differentiation.

It now remains to make mention of "Ozokerite," and the paraffinaceous group of native solid hydrocarbons.

**Ozokerite** or "Mineral Wax" is a waxy paraffinaceous solid bitumen, composed mainly of the higher members of the "$CnH2n+2$" and the "$CnH2n$" series of

hydrocarbons, and is generally found in association with petroleum of a paraffin base, from the alteration and inspissation of which it has arisen.

The colour of the crude material varies from a colourless or transparent yellow through yellow-brown and brown to a dark brown, or sometimes even almost black in appearance, according to the nature and amount of the impurities intimately contained in the wax.

The specific gravity is just under unity, and the fusing-point ranges from about 150° to 180° F., but the substance frequently carries some petroleum in diffusion—which renders it softer and the fusing-point lower, according to the amount of petroleum present. It is soluble in most of the solvents — such as carbon disulphide, turpentine, petroleum distillates, benzol, etc., and also in ether, but only very sparingly soluble in alcohol.

Ozokerite is seldom found in formations older than the Upper Cretaceous, and is of more general occurrence in the Tertiaries and notably in the Miocene.

It usually occurs in fissures and veins, mixed with or impregnating a large amount of extraneous mineral matter—such as sands and clays, or the pulverized rock—such as that derived from sandstones and shales—filling dislocation-fissures ("fault-rock"). When thus intermixed with a substantial amount of extraneous mineral matter, the material is known as "lep." The ozokerite can be readily separated from such material by means of extraction with hot water. The mode of occurrence in the island of Tcheleken—as infilling the fault-fissures and impregnating the "fault-rock"—has already been described.

In some cases, however, it occurs fairly pure, in the form of minute veins or streaks, of a yellowish or yellowish-brown colour, in clays, and often following the small slip-

planes and cracks, sometimes thus forms a kind of network; while the surrounding clays are frequently impregnated to a considerable extent—from which the ozokerite can be extracted by means of hot water. In this manner it occurs in Galicia, where the associated strata and impregnated clays have been subjected to much disturbance, and the latter have become much fissured and cracked. Occasionally aggregations of the more or less pure substance are found, which have sometimes been separated out from the impregnated material and re-deposited in a purer condition by means of hot springs (as, *e.g.*, in Tcheleken).

In regions where a paraffinaceous petroleum occurs near the surface, small pieces or pellets of ozokerite, usually of a brown or dark-brown colour, are often to be found on the surface, or in the soil, thus affording an important indication—such being particularly manifest in arid countries with the surface barren of vegetation. Where, however, a paraffinaceous petroleum occurs in the deeper horizons only, as is the case in some fields, ozokerite is not thus found at the surface.

The more important known deposits of ozokerite are those discovered in the Carpathians and in Russia; of these the most commercially important are those worked in Galicia (Boryslaw, etc.) and in the island of Tcheleken. In the United States, deposits are found in Utah and Arizona. These all, for the greater part, belong to formations of Miocene age.

The principal uses of ozokerite, or "Ceresin"—as the refined substance is termed—are for the manufacture of candles, coloured pencils, ointments, and other medical purposes; while the product of "okonite" has a large use as an insulator—particularly in connection with cables, and "heel-ball" is another product manufactured from it.

"*Zietrisikite,*" named after Zietrisika, in Moldavia, where it is found, is a variety of ozokerite, but differs in being almost completely insoluble in ether and in having a higher fusing-point; in colour it is a deep red-brown. A similar substance is also found in Slanik, Moldavia. "*Neft-Gil*" is another species of ozokerite found in the island of Tcheleken, and similar or related to Zietrisikite, although to a small extent soluble in ether; it is of a chocolate-brown colour. While another wax-like substance analagous to ozokerite, which has been termed "*Baikerite,*" is found in the neighbourhood of Lake Baikal (Siberia).

Certain wax-like hydrocarbon substances, related to ozokerite, are found in beds of coal, lignite, and peat; among these occurrences mention may be made of the following, that have received names. "*Hatchettite,*" which is named after C. Hatchett, a chemist, is a crystalline wax which was originally found in a peat-bog on the borders of Loch Fyne, Argyllshire, and also occurring in the Coal-Measures near Merthyr-Tydvil, in Glamorgan. It is of a yellow colour and fuses in the neighbourhood of 120° F.; it is slightly soluble in ether and boiling alcohol, but more soluble in boiling ether. A similar species has also been recognized as occurring in the coal-beds of the Carboniferous at Rossitz in Moravia, where it is associated with another mineral which has been named "Valaite," but this appears to be more of the nature of a resinous substance.

"*Scheererite*" (named after Capt. Scheerer) occurs in a Tertiary bed of lignite containing trunks of pines and other trees, at Uznach, near St. Gallen, in Switzerland. It is in a crystalline form, and of white, grey, yellow, and pale reddish colours, fuses at about 110°-115° F., and is soluble in ether and alcohol.

"*Könlite*" (named after Herr Könlein) is another

variety found in the brown coal in the same locality as the preceding, while also occurring associated with "Fichtelite" and fossil pines in peat in the Fichtelgebirge, near Redwitz (Northern Bavaria), and differs from Scheererite in undergoing transmutation by distillation, while it is only slightly soluble in alcohol, but more soluble in ether, and is reddish-brown to yellow in colour, the fusing-point being at about 114° F.

"*Fichtelite*," which takes its name from the Fichtelgebirge, where it is found, as above stated, in peat near Redwitz, in association with fossil pines, is white and translucent; is readily soluble in ether, but less so in alcohol, and fuses at a low temperature. A similar variety has also been found in peat-mosses elsewhere, generally associated with fossil pines, including some instances in Great Britain. "*Hartite*" is found in brown coal or lignite, associated with fossil pines, at Oberhart, near Gloggnitz, which is not far from Vienna. It is similar to Fichtelite in appearance and solubility, but differs by its higher fusibility, melting at about 166° F.

"*Ixolyte*" (from ἰξός, gluey, and λύειν, dissolve) resembles the preceding variety, with which it is associated in the lignite at Oberhart, but differs in having a higher fusing-point and a hyacinth-red colour (but when pulverized the colour becomes ochre-yellow or yellowish-brown).

"*Dinite*" (named after Prof. Dini, by whom it was discovered) is found in a bed of lignite at Lunigiana, Tuscany (Italy), and occurs in crystals which are clear or translucent with a yellowish coloration, and is fragile; it is soluble in ether and slightly so in alcohol.

Lastly, pure native crystalline solid paraffin is sometimes found occurring in cavities in basaltic lavas; as, for instance, near Paterno, in Sicily.

# APPENDIX.

## GEOPHYSICAL METHODS AS APPLIED TO OIL-FINDING.

By M. Muhlberg, Ph.D.
(Aarau, Switzerland).

The author wishes to record his obligation to Prof. J. Kœnigsberger for having kindly revised these pages.

Contents.—**Introduction**—(1) **Determination of the Distribution of Masses of Rocks of Unequal Gravity by Means of the Torsional Balance**—The Purpose of the Rotating Torsional Balance—The Principal Features of the Apparatus and of the Method—What can be investigated by this Means in Oil Practice—Some Details concerning the Mode of Procedure and the Operation of the Instrument—The Hecker Model—Instances of where the Torsional Balance has been applied—Discussion of the Special Cases in Oil Practice. (2) **Magnetic Surveying**—The First Geophysical Means of Prospecting introduced in Mining—Use of the Sensitive Instruments in Practical Oil Geology, and Differentiation of the Rocks by means of their respective Iron Contents—Magnetic Anomalies in American Oilfields—The Components of the Terrestrial Magnetic Force that should be examined in the various Cases—Examples of executed Magnetic Surveys—Method of Professor Koenigsberger in order to make Observations independent from the Time-variations of Terrestrial Magnetism—Magnetic Surveys cheaper and quicker than those with the Torsional Balance, while applicable in all kinds of country, although results generally more difficult to read—Instruments for most Accurate Observations—Co-operation of Gravimetric with Magnetic Surveys. (3) **Electrical Methods**—Differentiation obtained when introducing an Electrical Current into a Non-Homogeneous Subsoil—To find the Strike of Strata and of Faults, and the Position and Form of Anticlines—Professor Schlumberger's Method of Equipotential Curves, and the Method by Testing the Electric Resistance—Instance of such a Survey Accomplished—Restrictions to the Method and Corrections for Irregularities of the Surface—Particulars of the Method for determining the Delimitation of Strata

beneath an Overburden—Determination of the Border-Line between Oil and Water. (4) **Prospecting by Means of Seismic and Acoustic Waves**—The Seismic Method of L. Mintrop—Its Uses and Mode of Operation—Development of Acoustic Methods. (5) **Determination of Underground Temperatures**—The Small Rate of Increase of Depth per Unit of Temperature in Oil-Wells as a Criterion for the Prospects of finding Oil—The Various Circumstances influencing the Geothermal Gradient—Darton's "Geothermal Data of the United States"—When and where Measurements should be made—Observations in other Respects. (6) **Other Investigations and Tests**—Determinations of Radio-activity and Detection of Faults and Oil-bearing Strata—Collecting and Testing the Smallest Traces of Gas—Examination of Waters for discerning various Water-horizons—Testing Damaged Packings in Wells by pouring in Solutions of readily discernible Substances—List of Geophysical Literature.

## Introduction.

THE geophysical methods have been introduced into oil-practice as an additional means of investigation to geological prospecting—namely, in such cases where, owing to an overburden concealing the features concerned, the usual geological researches cannot secure sufficient evidence. It is the tectonic circumstances favourable to the storage of oil that most of the methods are intended to ascertain, although a few of them aim at testing the presence of oil or its distribution on the basis of its physical properties. Like geological surveying, geophysical prospecting is suited to the elucidation of whole tracts of land, unlike, *e.g.*, that by test-borings, which merely clear up particular spots.

The methods are founded on the variability in distribution among the rocks of certain physical properties—as the specific gravity, the magnetic and the electrical properties, the elasticity, the temperature, and also the radio-activity. Except in the case of the latter, these properties have an action, and can be tested or ascertained at a distance, so that, as far as the main methods are concerned, the observations can be taken at the surface of the Earth.

A few other means of investigation in oil-practice are mentioned for the sake of completeness in this matter.

### 1. Determination of the Distribution of Masses of Rocks of Unequal Gravity by means of the Torsional Balance.

The rotating torsional balance, of the model of the Hungarian physicist, R. v. Eötvös, who found a new principle by starting from the ideas, inventions, and implements of Isaac Newton, John Mitchell, and Henry Cavendish, is an instrument of great sensibility to the variations of gravitation, and is used to ascertain and to determine the disposition of unequal distribution of gravity in the crust of the Earth.

The balance-arm is suspended from the torsion-head of the instrument by means of a long and very fine wire of platino-iridium; at one end of the balance-arm one of the weights is suspended by a long wire, so that it swings about 50 cm. below the balance-arm. Wherever the force of gravity is unequally distributed in the neighbourhood of the torsional balance, the weight which is hanging lower will be deflected into the direction of the greater gravity; the balance-arm will rotate with its suspension-wire. Eötvös has combined two balances, in opposite disposition side by side, in one double apparatus, which arrangement allows of executing at once two determinations in opposite directions. In order to determine the position of the heavier, and also of the lighter mass, and to measure the amount of the variation of attraction in a station, the whole double-instrument must be brought into three different positions of the compass by rotation around the axis, and in each position the eventual difference between the rotation of the instrument and the actual rotation of the balance-arm is determined by observation of a scale.

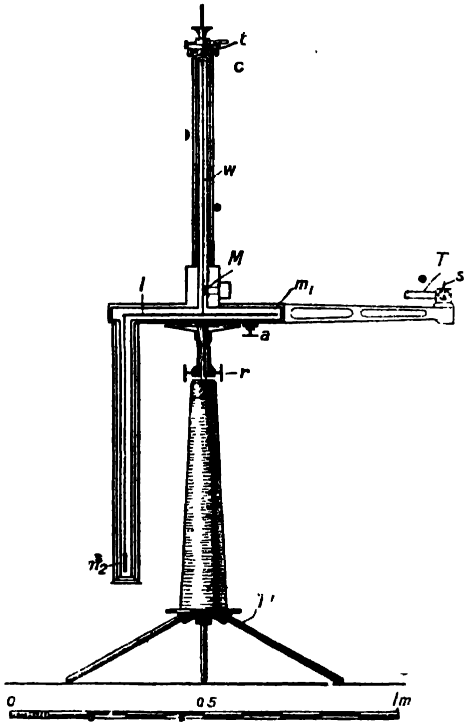


Fig. 28.—The Eötvös Rotating Torsional Balance.

After a sketch by Prof. Eötvös for explaining the principles (showing only one balance).

*c*, Threefold aluminium-casing of the instrument.
*t*, Torsion-head, to which the system is permanently adjusted.
*w*, Wire of platino-iridium.
*l*, Balance-arm.
$m_1$ and $m_2$, The two weights.
M, Mirror, fastened to the balance-arm, which reflects the scale.
*s*, Scale, whereby the oscillations of the mirror are read.
T, Telescope.
*a*, Arresting device.
*r*, Revolving device for the whole apparatus.
T', Tripod of the apparatus.

The variation in gravity is expressed in absolute units "C.G.S."—*i.e.*, the unit of centimetre-gram-second (*Dyne*).

The model of Prof. Hecker (see Fig. 29), which is of particular value for practical purposes, shows an accuracy of $5 \times 10^{-9}$ C.G.S. per 1 mm. division of the scale calculated for a distance of 50 cm. from the scale; $1 \times 10^{-9}$ can easily be attained.

Small masses which are near by have the same influence as large ones at a distance. Isolated rocks and aggregates of shifted rocks lying near or contained within fine material, as may occur with glacial deposits, will have a disturbing influence if they are situated near the observation-station. By using double or treble positions at distances of 30 to 60 feet, the question can be solved whether the variations of attraction are due to large masses at a distance or to small inclusions near by. Therefore, in order to save time, it is advantageous to operate with two double-balance apparatus at the same time.

The flatter the surface of the soil the better. Up to the present date the rule has been that measurements with the torsional balance were only quite satisfactory in flat country, and that only small unevenness of the surface could be corrected by calculation, so that surveys in tracts of lands with inclinations of over 5° were not accurate or might even give rise to wrong conceptions. These difficulties have now been overcome by Professor Kœnigsberger. Measurements at Andermatt, in the Swiss Alps, where the thickness of the gravel deposits filling the valley has been ascertained, and in the Black Forest where the depth of the Lake Titisee has been tested, have proved that the torsional balance can also be made use of among mountains.

The distance from one station to the other must be chosen according to the probable dimension and position

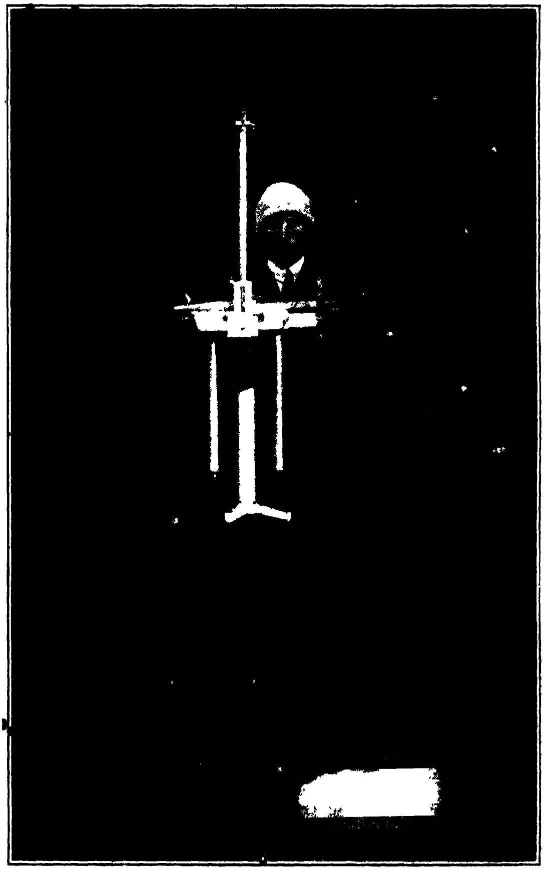

Fig. 29.—The Hecker-Model of the Torsional Balance.
(Showing the complete double-apparatus.)

On the right side is seen the arrangement for the photographic registration.

disturbance. It is a peculiarity that sinking temperatures cause less disturbance than rising ones. The measurements, therefore, formerly used to be made exclusively or mainly at night-time. The Hecker model of torsional balances, in its newest form, is adapted for use in daytime. Once prepared, the whole operation can be carried out automatically. The registration of the positions of the balance-beams in the different azimuthal positions of the instrument is done photographically. The model mentioned, however, allows visual readings also to be taken. Owing to the automatic registration one man can at the same time take charge of more than one apparatus, whereby time and salaries can be saved by using two or three instruments.

One station requires, according to the accuracy intended, from 3 to 6 hours.

While the first model of the Eötvös balance and other large ones require a cart for transport, or, for short distances, two men, the new small model mentioned above is—although being of equal sensibility—of such light weight that it can easily be carried by one man (Fig. 29).

The importance of the torsional balance as a means of prospecting for oil and gas deposits was first found out in Hungary. The Hungarian geologist, Prof. H. von Böckh, has shown that the anomalies of gravity along the Máros River in Transylvania, measured by Pekar and Fekete under the supervision of Eötvös in 1912, are to be explained by salt-domes. Upon these salt-domes prolific deposits of gas are found.

Later, H. v. Böckh had the surroundings of Egbell, in the March plain, in Hungary (now Gbley, forming a part of the Czecho-Slovakian State), examined with the torsional balance. This oilfield is situated in slightly folded strata of the Upper Tertiary, which—as the

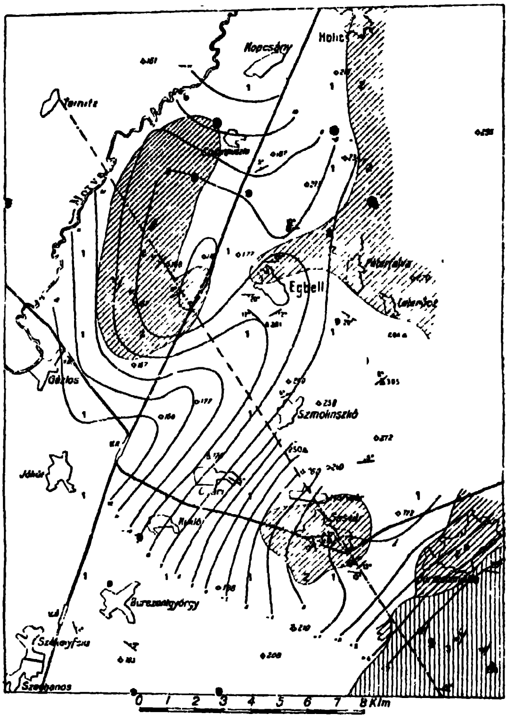


Fig. 30.—Geological and Gravitometrical Map of the Environs of Gbely (Egbell), in the plain of the Morva (Czecho-Slovakia).

After H. von Böckh.

1 inch = about 4 English miles.

1 (blank) = Pontian, 2 (diagonal hatching) = Sarmatian, 3 (vertical hatching) = Mediterranean deposits.

5° = strike and dip of strata. -ϕ-170 = altitudes in metres above sea-level The curves are the Isogams—lines of equal gravity.

The centre of the oilfield, which would make only a small spot on this map, is situated immediately to the north of the intersection of the diagonal (— - — - —) line with the railway track, in an area where a maximum of gravity has been ascertained.

author would assume—unconformably overlap risings of older Tertiary strata, which are of higher specific gravity and more dislocated. The oilfield exists in the determined area of maximum-gravity.

Subsequently, the use of the torsional balance has been introduced into Germany, Austria, Roumania, Egypt, Canada, Texas, and other countries. Besides its use in prospecting for oil, it is also applied to other practical purposes. Several oil companies have engineers and geologists specially trained for this work.

The special cases in oil-practice are :—

Ordinary anticlines and domes. In many cases there will exist a difference of gravity between the inner and outer strata of a fold. This will apply to folds with such younger strata as are less consolidated than the older ones in the core. The central part of the anticline will then be discernible as having the maximum of gravity. Gbley (mentioned above) is an example thereof.

Oilfields above "buried hills." S. Powers recommends in *Economic Geology*, 1922, measurements with the torsional balance and seismometric observations as the best means for finding the "buried hills," which are of such importance in the American Mid Continent.

Plutonic intrusive masses in the form of laccoliths, dykes, etc., with which, *e.g.*, in Mexico, oil is often associated, will easily be traced with the torsional balance.

Large lenses of oil-sand between clays are determinable on account of the higher specific gravity of the sand.

Salt-domes belong to the geological type of deposits which are easily determined with the torsional balance, on account of the comparatively great difference of density between salt and surrounding rocks, as well as on account of their characteristic form ; they have a minimum of density.

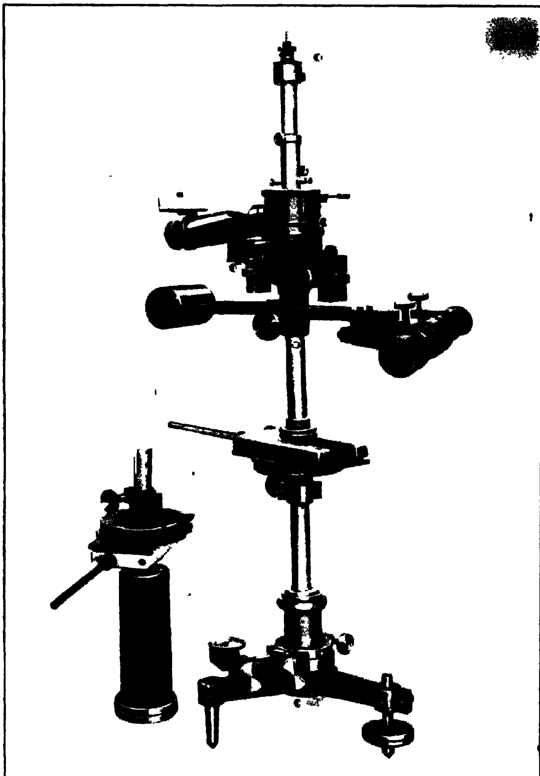

Fig. 31.—Universal Magnetic Variometer.

Instrument of highest sensibility, used mainly for the determination of the variations of the declination and of the horizontal intensity of terrestrial magnetism, while it can also serve for determining the variations of the vertical intensity, which is required when locating the depth of the border-plane between magnetically different masses.

The compass-needle is suspended on a thin wire of platino-iridium. The readings are effected with a telescope, mirror, and scale. The sighting is done with a telescope.

The deflecting magnets, that are necessary to compensate the horizontal component of the terrestrial magnetic force, are contained in the light-coloured aluminium box—appearing in the lower part of the instrument in the figure—which can be moved along and around the vertical axis of the instrument.

The position and the inclination of monoclines can be determined on the same assumptions as anticlines.

The fact that faults can be located by the torsional balance, if the strata displaced have different specific gravities, has been proved very distinctly by the surveys of Prof. R. Schumann in the Vienna Basin.

## 2. Magnetic Surveying.

The magnetic properties of minerals and rocks were the first to be the object for the application of physical means of prospecting in practical geology. For decades iron ores (magnetite) were prospected by means of magnetic instruments, especially in Sweden, where these methods originated. Most sensitive instruments, such as have been perfected in the last few years, can also be of use in practical oil-geology.

The magnetic method is adaptable to many geological conditions, for which the torsional balance can also be used. Its use is founded on the fact that most rocks contain iron compounds, and that, on the other hand, they are sufficiently differentiated in relation to their iron contents.

The difference of ordinary sedimentary strata, as compared with rock salt, which is free of iron and is diamagnetic, is appreciable to sensitive instruments. Basaltic dykes and laccoliths of diorite are quite noticeable. Diorite will almost invariably have definitely stronger magnetic properties than sediments, such as clay, limestone, etc., on account of the finely distributed magnetite that it contains.

G. F. Becker has called attention to the fact that oil-fields in the U.S.A., especially in the Appalachian district, are characterized by magnetic anomalies of the declination. More often than is known, anticlines may be

connected in some countries with magmatic intrusions which would be magnetically noticeable.

Magnetic prospecting can be directed to the amount of the horizontal and the vertical components of the magnetic field of the Earth, measured absolutely or relatively, as well as to the angles of declination and inclination. For the complete determination of the terrestrial magnetic force three of these elements must be known—viz., vertical intensity, horizontal intensity, and declination—which together give the additional force to the force of the Earthfield, lying in the strongly magnetic masses. For practical purposes, however, generally one or two elements are sufficient. Which of the two components of intensity should be chosen, depends on the ratio of surface-development to the situation in depth, and also on the vertical dimensions of the object in view, which differs magnetically from its surroundings.

The anomaly of the vertical component has its main development practically in the middle of the masses of magnetic differentiation, while the anomaly of the horizontal component is mapped as a broad border around them. The disturbances of the horizontal intensity and the declination are noticeable over a larger area in the case of narrow objects; therefore, the determination of the horizontal intensity is advisable in this instance.

The field of salt-deposits in S.W. Mecklenburg (North Germany) was surveyed in 1920 by F. Schuh, with the field-balance of A. Schmidt, in relation to the vertical intensity; this instrument, which is a considerably more accurate form of the "dip-needle" used in North America, measures the relative amount of the vertical magnetic component. Another salt-line in North Germany was successfully prospected with a horizontal

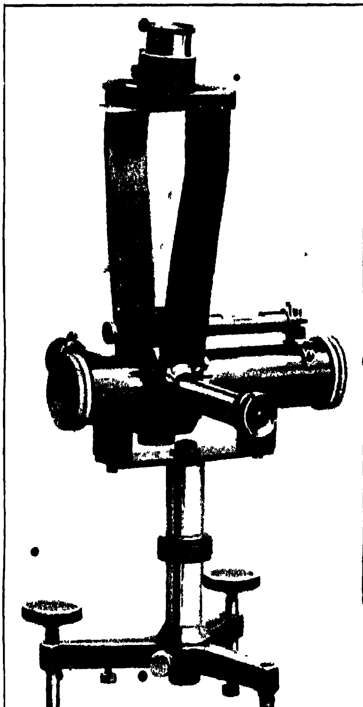

Fig. 32.—Relative Inclinator (magnetic field-balance, or improved "dip-needle"), for quick and accurate measurements of the local variations of the magnetic inclination.

A light magnetic needle, swinging in a vertical plane, is attached to a thread, which is kept stretched horizontally with equal tension. The inclination of the needle is observed by a telescope, mirror, and scale.

variometer. The relative surveys are done in less time than the absolute ones.

Fig. 33.—Map showing the Lines of Equal Vertical Magnetic Intensity in the Area of the Salt-Deposits of South-western Mecklenburg. Determinations by Dr. Fr. Schuh, 1920.

The difference between the lines of equal intensity is 10 $\gamma$ (1 $\gamma$ = 0·00001 C.G.S.).

The darker tinted the areas (being also small values of magnetic intensity), the nearer to the surface are the gypsum and salt-deposits of the saline domes. The closer the lines the steeper are the slopes of the saline domes.

o I, etc. = bore-holes.

Scale, 1 inch = 3·6 miles.

All absolute and relative methods used up to date have the drawback that the time-variations of terrestrial

magnetism make themselves fully felt, and, therefore, necessitate corrections based on the curves obtained from magnetic observatories.* These curves, however, are not delivered daily, and at a greater distance from the observatory the actual time variations do not agree with those registered at the observatories; over wide regions there are no observatories at all. Prof. Kœnigsberger has, therefore, worked out a method which makes the measurement of the magnetic components independent of time; † the measurement of the relative declination now can be executed independently of the weather, and in an exact manner in any region.

The magnetic surveys require much less time and cost than those of the torsional balance, while they are applicable in hilly country, on soft, swampy ground, on water, and in dense woods Their results, however, are generally more difficult to read than those of the torsional balance. With the most exact horizontal variometers one station requires 15 to 20 minutes for putting up the instrument and taking the readings, with very exact variometers 10 minutes.

In conjunction with the gravitometric surveys, Professor Eötvos always made also magnetic surveys, and found that they give a good control for each other and corroborate results. In new regions of wide extent, it will be advisable first to prospect magnetically on a large scale, and, if anomalies appear, afterwards to examine the interesting places more closely with the torsional balance.

* *i.e.*, if very exact observations are required.

† This is a simple method of observation, operating two similar instruments at the same time.

### 3. Electrical Methods.

**Differentiation obtained when introducing an Electric Current into a Non-Homogeneous Subsoil.**—Under favourable circumstances the strike of strata and of faults can be determined through an overburden concealing them by means of electrical prospecting, which was first developed by Prof. Schlumberger for ore-prospecting. It may even be occasionally possible by such means to find out the position and form of anticlines. The possibility principally depends on the unequal distribution, in the subsoil, of the humidity, which is electrically conductive. Water generally collects along the joints of the strata, and often follows faults, while differently distributed in rocks of different porosity. Consequently the electric conductivity is greater in a direction parallel to the stratification than across it. To determine this distribution the equipotential curves (or in some cases the variations of the electric resistance) of an electric field which is brought to the place prospected can be traced and mapped. The electric current necessary for this is conducted to the soil by means of primary electrodes, which are far apart from each other (as far as a mile), and to which the current is brought by insulated wires. While in homogeneous soil a distinctly symmetrical field of equipotential curves is obtained, this is deformed and rendered unsymmetrical by inequality of conductivity. The curves adapt themselves more or less to the strike of the stratification or to a fault.

The electric current used may be direct, or, better still, an alternating current. The current can be taken off a small generator of high frequency, specially manufactured, which is worked by hand or by a small petrol motor. One man is quite able to carry all the parts of the outfit for using this method.

The primary electrodes can be point-electrodes (Schlumberger) or line-electrodes (Lundberg-Nathorst).

The equipotential curves can best be determined by using a telephone connected to the secondary electrodes, and equipped with an intensifying apparatus.

The machine and the rest of the outfit, such as sold by the several firms, must be tuned with each other to give the best results.

One of the secondary electrodes remains in place while the operator seeks, by means of the other secondary electrode, those places which show the same potential as the first one. In all such places the sound in the telephone, otherwise constantly heard, disappears.

An equipotential curve can be followed for a length of 600 feet in one hour in distances of 30 feet. Thus several lines are examined. In a month it is possible to survey up to about 10 English square miles. This depends, of course, on the accessibility of the surface. According to the latter and to the nature of the soil the method must be modified in details.

The steeper the incline of the strata and the less overburden there is, the more obvious the results will be. Prof. C. Schlumberger has observed, by this means, in Normandy the strike of steeply inclined Palæozoic strata under an overburden of flat Jurassic formation of 200 to 300 feet in thickness. The usefulness of the method also depends, of course, on the humidity. The overburden should preferably consist of equally mixed and slightly humid material without horizontal alternation of parts with different humidity. Completely dry countries (desert) present great difficulties. Rugged country necessitates corrections. Complications of this nature can be corrected by using the modelling method—*e.g.*, that adopted by the Swedish scientists Bergström and Bergholm.

The outcrops and delimitations of strata of unequal

[To face p. 216.

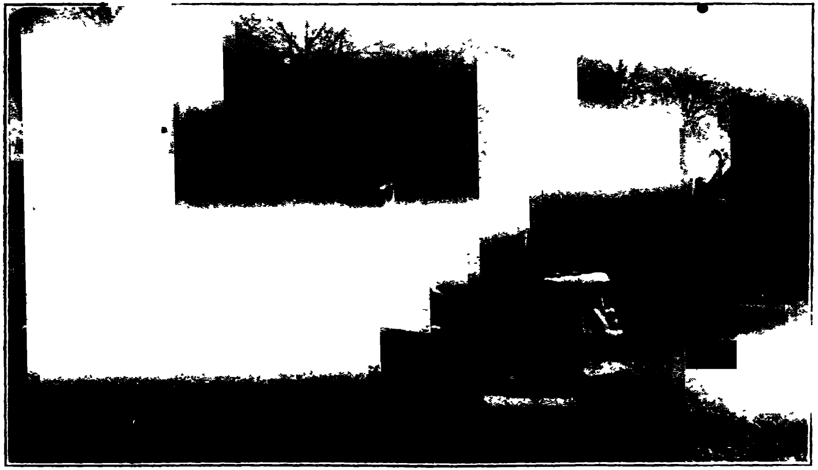

Fig. 34.—Operators determining Equipotential Lines.

The apparatus in the foreground is a combination of an electrical generator with a benzol-motor.

conductivity, for instance (to quote Prof. J. Kœnigsberger), of an inclined oil-sand, situated beneath an overburden, reveal themselves by the strong alternation of the equipotential curves, or even better in the variations of the electric resistance. The accuracy with which the local position of such a border line can be determined is about proportional to the depth of the outcrop of the strata—*e.g.*, the determination would be possible, under an overburden 50 feet thick, with an accuracy within 20 to 50 feet in a horizontal direction across the line of strike.

Should the position of a given stratum be known exactly at a certain point, then its continuation, in the direction which has been determined geophysically, is thereby more exactly localized.

The outcrop of an oil-deposit which has already been found by boring can often be determined by this method.

A further problem that can be solved, under favourable conditions, by means of electrical methods, is the determination of the border-line, within an oil-horizon, between the oil and the surrounding water. The oil-horizon concerned must not be superimposed either by another oil-bed or by water.

### 4. Prospecting by Means of Seismic and Acoustic Waves.

The method of seismic waves, as developed by L. Mintrop, makes use of the variation in the elastic properties of different rocks. The transmissive velocity for seismic (as also acoustic) waves is different in various media—*e.g.*, loose sands or clays would transmit such waves much more slowly than solid rocks. It is possible to calculate fairly well the position and depth of the border-planes between two masses of rocks which are

elastically differentiated by means of the seismic waves produced by violent explosions. The times of arrival are recorded seismographically. In oil-geology the main objects for such methods have been salt-domes.

Supposing a deposit of less density were lying flatly (or in a shallow depression) on the top of rocks of greater density, then the seismic or acoustic waves produced at a place on the surface will be transmitted along different paths—viz., (1) through the air, (2) along the surface through the looser deposit, (3) along the limits of the latter against the denser rock, from which deflected waves also originate and can be recorded, and (4) through the deeper rocks—although these are difficult of observation. The waves run most rapidly through the latter, and most slowly through the air; the surface-wave is weak; the route through the border-plane of the underlying strata, and from it to the surface, is the longest. If, however, the distance of the receiving station is chosen far enough from the sending one, the waves running along the underlying strata will reach the receiving station first. The greater the distance along which this ratio prevails, the thicker the looser upper layer will prove to be.

In the case of a convex salt-dome the waves originating from its upper limiting surface will be recorded.

Along the section to be investigated a series of receivers (Pendulum-seismographs) are put up; the experiment is repeated along a number of sections. The method, therefore, is expensive; however, it gives an important supplement to the results obtained by the means formerly mentioned, and it can, in favourable cases, give results down to 2,500 feet. The method fails in the case of steeply inclined strata.

The methods using acoustic waves are being developed for different special cases of tectonic geology.

## 5. Determination of Underground Temperatures.

Many years ago experience established the fact that oil-deposits commonly show a comparatively high temperature. Many observations of temperatures taken in the depth of bore-holes or of the fluids flowing out of them show a comparatively rapid increase according to depth, thus a small geothermal gradient—*i.e.*, the rate of increase of depth per unit of temperature. This fact can be used as a criterion of the prospects of finding oil in a bore-hole in operation. The determinations must, however, be made carefully and amply, and the results valued with due consideration of all influencing circumstances.

Many data of temperature measurements in or at bore-holes and mines are not reliable as being the real Earth temperature at the particular spot. Concerning oil-borings, *e.g.*, it can happen that gas lowers the true temperature in consequence of the cooling action of dilatation; too low a reading will also be obtained from determinations of temperature taken instead of at depth in a flow of water at the top of the bore-hole, when the water was subject to cooling during its ascension. A large number of sufficiently reliable data, however, have been published, from various descriptions of geological situations, which show that the geothermal gradient may differ in different places, as well as vary with the depth in the same locality. The reasons are manifold—increase of temperature by neovolcanic influences, by ascending hot water, by chemical metamorphosis of minerals such as coal, oil, sulphides, anhydrite passing into gypsum, and coolness produced by large rivers, lakes, or the sea, as also infiltrations of water.

The unequal thermal conductivity of the rocks is also

determinative. The amount of dip in the case of ordinary sedimentary strata is of less consequence than in the case of dynamo-metamorphic schistose rocks. The saturation of the rocks with water or oil, of course, also affects the geothermal gradient. As well as the more local variations, there would apparently also be those of a regional nature. About 60 feet for 1° F. is considered as a normal geothermal gradient—*i.e.*, in absence of local cooling or heating influences and in rocks of mean thermal conductivity. However, a critical selection of 15 oil-borings of more than 1,000 feet depth from Darton's "Geothermal Data of the United States" results, for instance, in a mean of about 41 feet for 1° F., in respect of those places and depths tested.

In order to ensure practical advantage in each case from the determinations of temperatures, it is generally not sufficient to undertake merely one observation at the depth casually reached when a decision as to the continuation of the bore-hole has to be taken. On the contrary, it is necessary to take observations, while sinking the well, systematically at intervals of, say, 200 to 300 feet, or rather, whenever another group of strata showing different lithological characters, or a water- or oil-bearing bed is reached. For it is not simply a question of the mean geothermal gradient, but equally that of the values obtained for the single subdivisions, of the details of the temperature-curve, or of the geothermal-geological diagram. Thus a geothermal gradient which in its total is low need not, for instance, necessarily mean a heat-producing deposit—*e.g.*, an oil-deposit subjacent to the position of measurement. Such may also have been caused by a heat-producing stratum at a higher horizon. The less a region has already been thermally elucidated, the more desirable are frequent temperature measurements. The trifling cost and trouble

should not be avoided to procure data allowing, in case of need, conclusions of practical use to be drawn. Systematic temperature measurements ought to-day to be included in the procedure of deep sinking. It may be mentioned that they can also be used to determine whether a flow of water in a boring originates in a new horizon or descends from a former water-bearing stratum, the water having broken in again. Moreover, temperature-measurements repeated from time to time in producing wells will sometimes furnish other useful information as to the conditions obtaining in the reservoirs.

### 6. Other Investigations and Tests.

**Determination of radio-activity** can prove boundaries of rocks, faults, as well as oil-bearing beds, either on the surface or in borings. Effects from a distance, say of more than 2 feet, are excluded in this method. The radio-activity of some rocks shows considerable differences, and, owing to their radio-active substances being also contained in the weathered parts, the subjacent fresh rocks can be discerned by determining the radio-activity of their weathered superficial crust. In oil-practice, however, the method may seldom be required for such a purpose. But the circumstance that radio-active substances often accumulate on faults can be used for their discovery in borings. It will be further possible to make use of the fact that oil is connected with particularly rich absorption of radio-active emanations.

In such oil-fields, where it is important to discern faults or where it may happen that oil-beds have been passed in drilling, the well-samples should also be examined respecting their relative radio-activity. In bore-holes—where they are not cased—radio-active

emanation can also be collected with the apparatus mentioned below.

**Determination of Gas.**—It may sometimes be valuable to investigate a bore-hole for the occurrence of even minute quantities of gas. Prof. Kœnigsberger has constructed an apparatus whereby gases from any part of a bore-hole can be collected, sealed, and hauled up, so that they can be tested on the surface.

**Examination of Water.**—It is often a disputed matter whether a flow of water in a well originates from a new stratum, or rather from one penetrated higher up, the water having broken in again after having been artificially stopped. Oil-men are aware of the costs with which such cases may be connected. Under such circumstances the waters tapped should be examined and samples kept. Or the facts may be elucidated by pouring colouring, or other easily discernible matter, behind the casing that is shutting off the upper water-bed—at least if the packing is sufficiently damaged so as to let the testing solution pass. While this may also be found out by means of electrical methods.

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## ADDENDA TO APPENDIX.

**Magnetic Methods.**—With reference to the determination of the vertical magnetic intensity, there is now another instrument for the relative measurement of such, which has been recently devised and operated by Prof. J. Kœnigsberger.

**Electrical Methods.**—In connection with the determination of the equipotential lines (see p. 216), there should be added (after the second paragraph on p. 216), "When working at great distances from the primary electrodes, it is recommendable to use also a method tracing the lines of the electric current."

With reference to **Acoustic Methods** (p. 218), the methods using acoustic waves, such as have been devised by several investigators, so far serve more especially for prospecting ores and salt-domes: further developments and a wider application for them are to be expected.

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